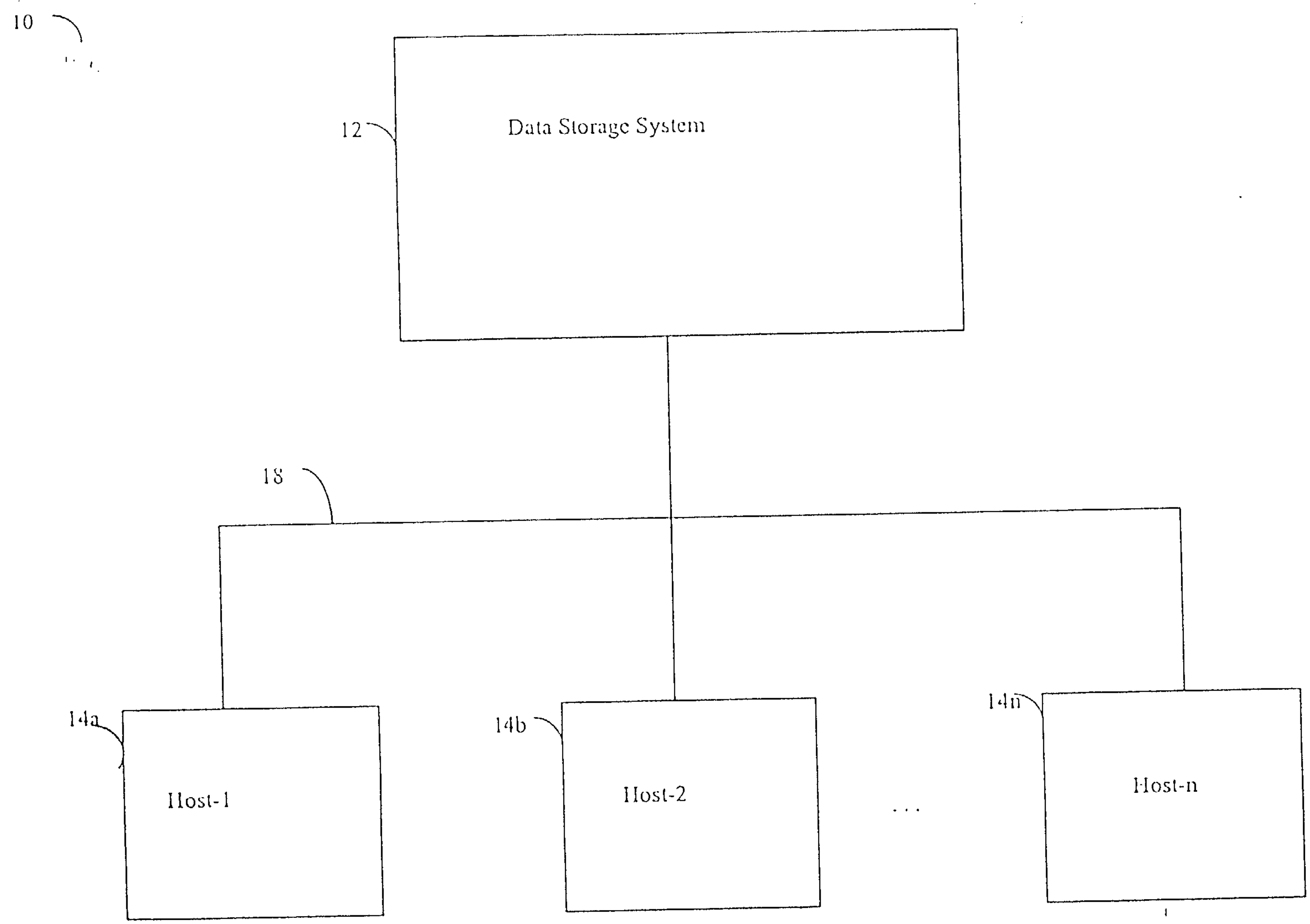


FIGURE 1

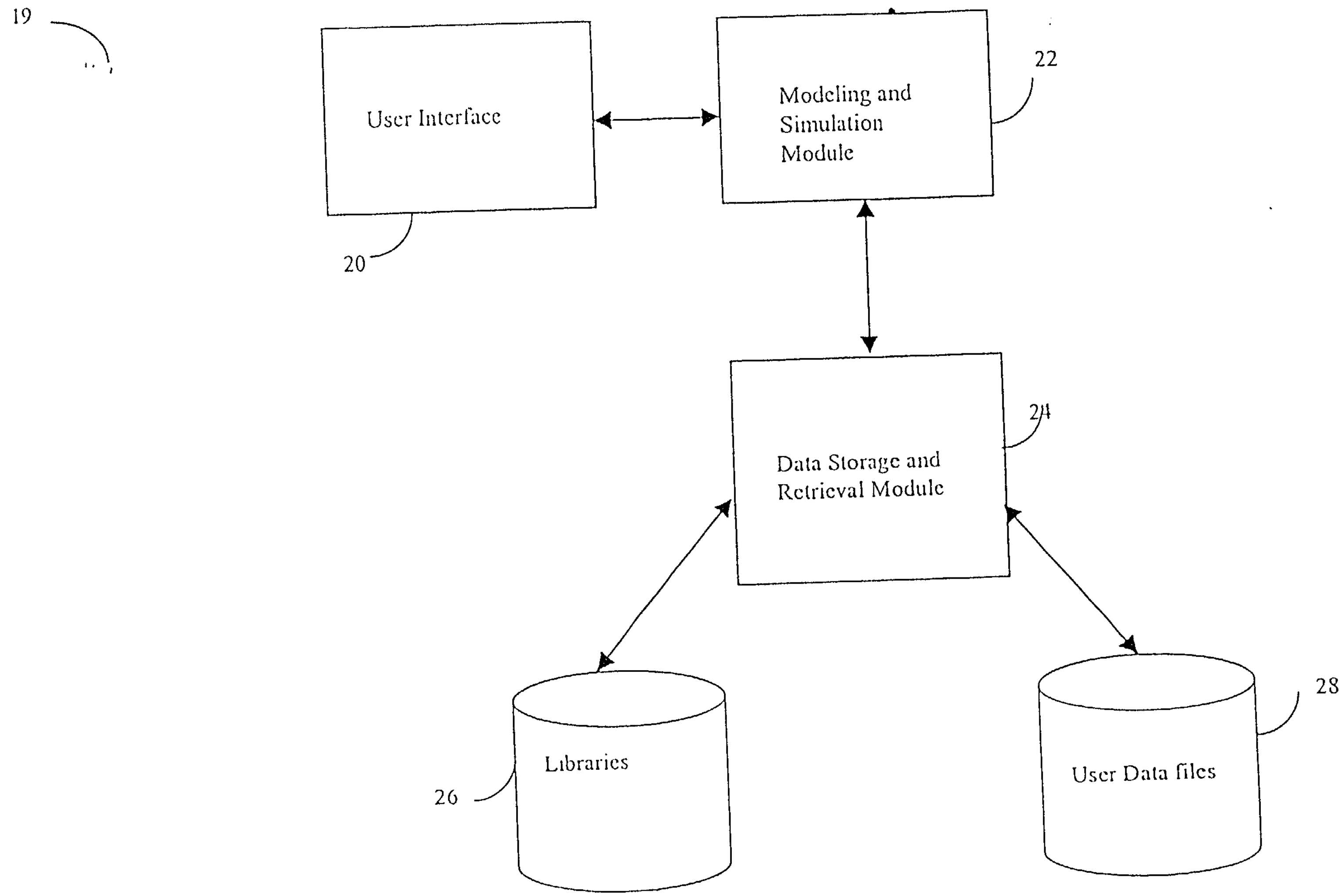

19
User Interface
20
Modeling and
Simulation
Module
22
Data Storage and
Retrieval Module
24
Libraries
26
User Data files
28

FIGURE 2

FIGURE 3

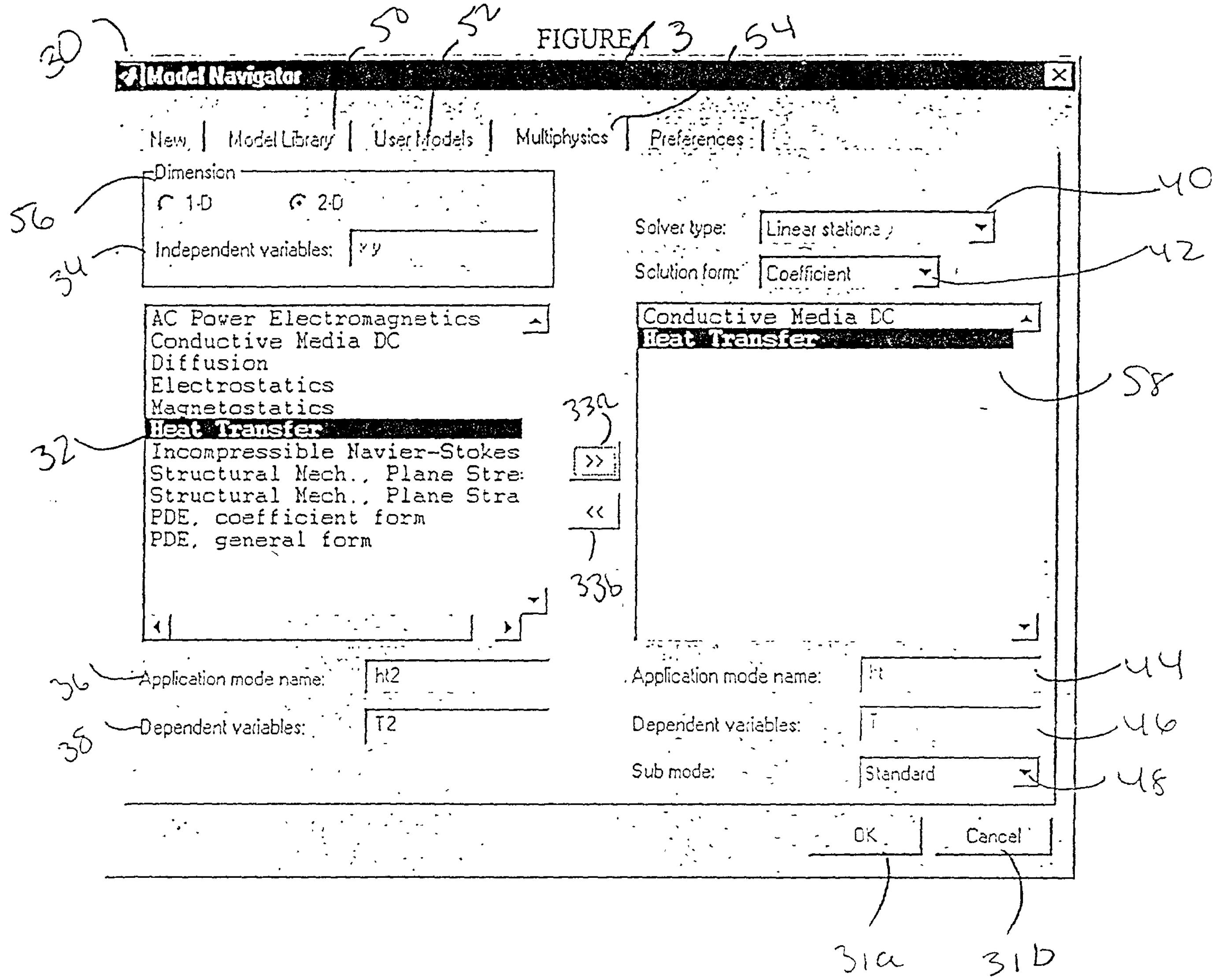

Model Navigator
New
Model Library
User Models
Multiphysics
Preferences
Dimension
1-D
2-D
Independent variables:
x y
Solver type:
Linear stationa
Solution form:
Coefficient
AC Power Electromagnetics
Conductive Media DC
Diffusion
Electrostatics
Magnetostatics
Heat Transfer
Incompressible Navier-Stokes
Structural Mech., Plane Stre
Structural Mech., Plane Stra
PDE, coefficient form
PDE, general form
Conductive Media DC
Heat Transfer
Application mode name:
ht2
Dependent variables:
T2
Application mode name:
Dependent variables:
Sub mode:
Standard
OK
Cancel
30
50
52
54
40
42
56
34
58
33a
32
33b
36
38
44
46
48
31a
31b

FIGURE ~~2~~ 4

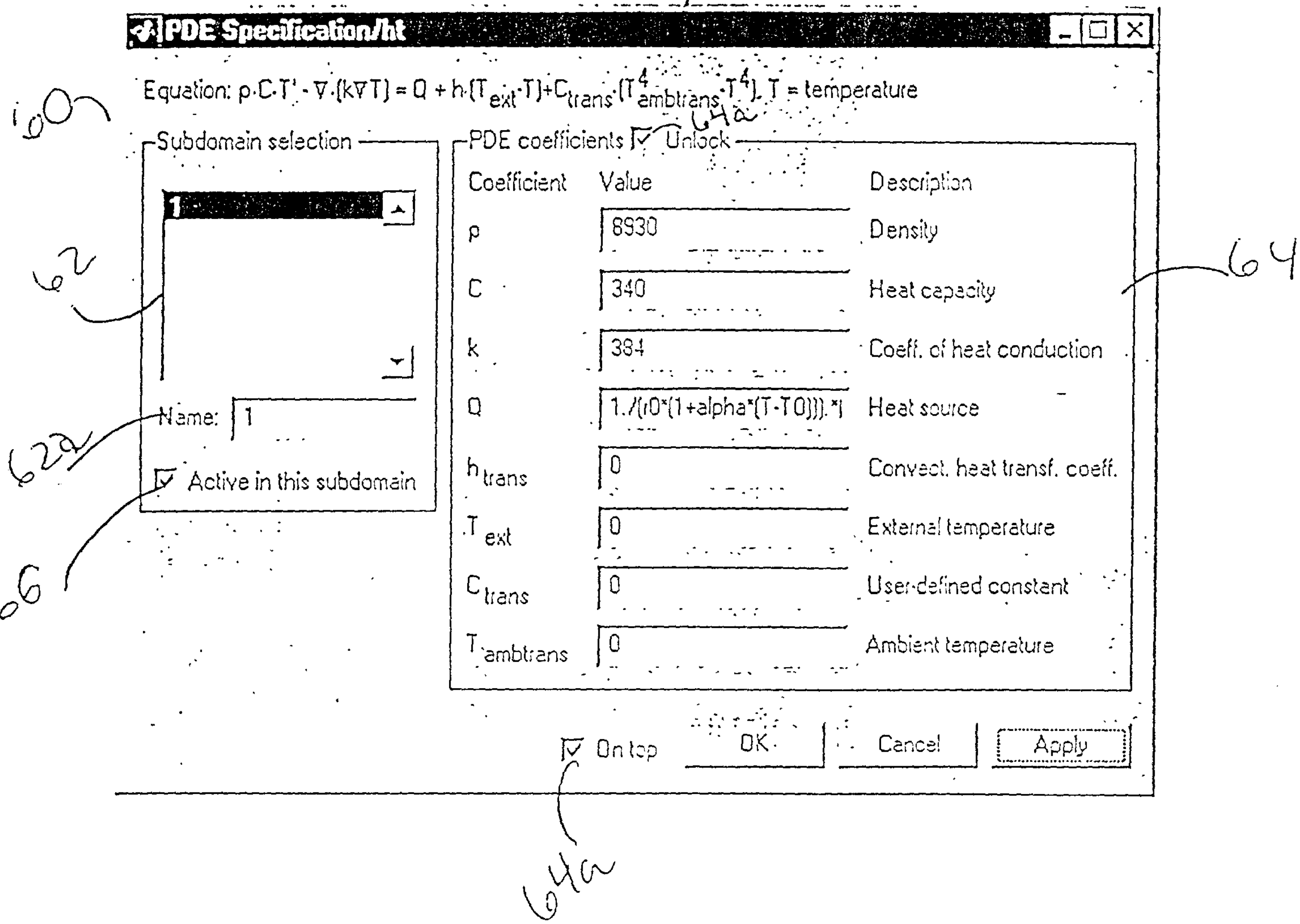

PDE Specification/ht
Equation: ρ·C·T' - ∇·(k∇T) = Q + h·(T_ext-T)+C_trans·(T^4_ambtrans-T^4), T = temperature
Subdomain selection
1
Name: 1
Active in this subdomain
PDE coefficients
Unlock
Coefficient
Value
Description
ρ
8930
Density
C
340
Heat capacity
k
384
Coeff. of heat conduction
Q
1./(r0*(1+alpha*(T-T0))).*(
Heat source
h trans
0
Convect. heat transf. coeff.
T ext
0
External temperature
C trans
0
User-defined constant
T ambtrans
0
Ambient temperature
On top
OK
Cancel
Apply
100
62
622
66
64
64a
64a

FIGURE 5

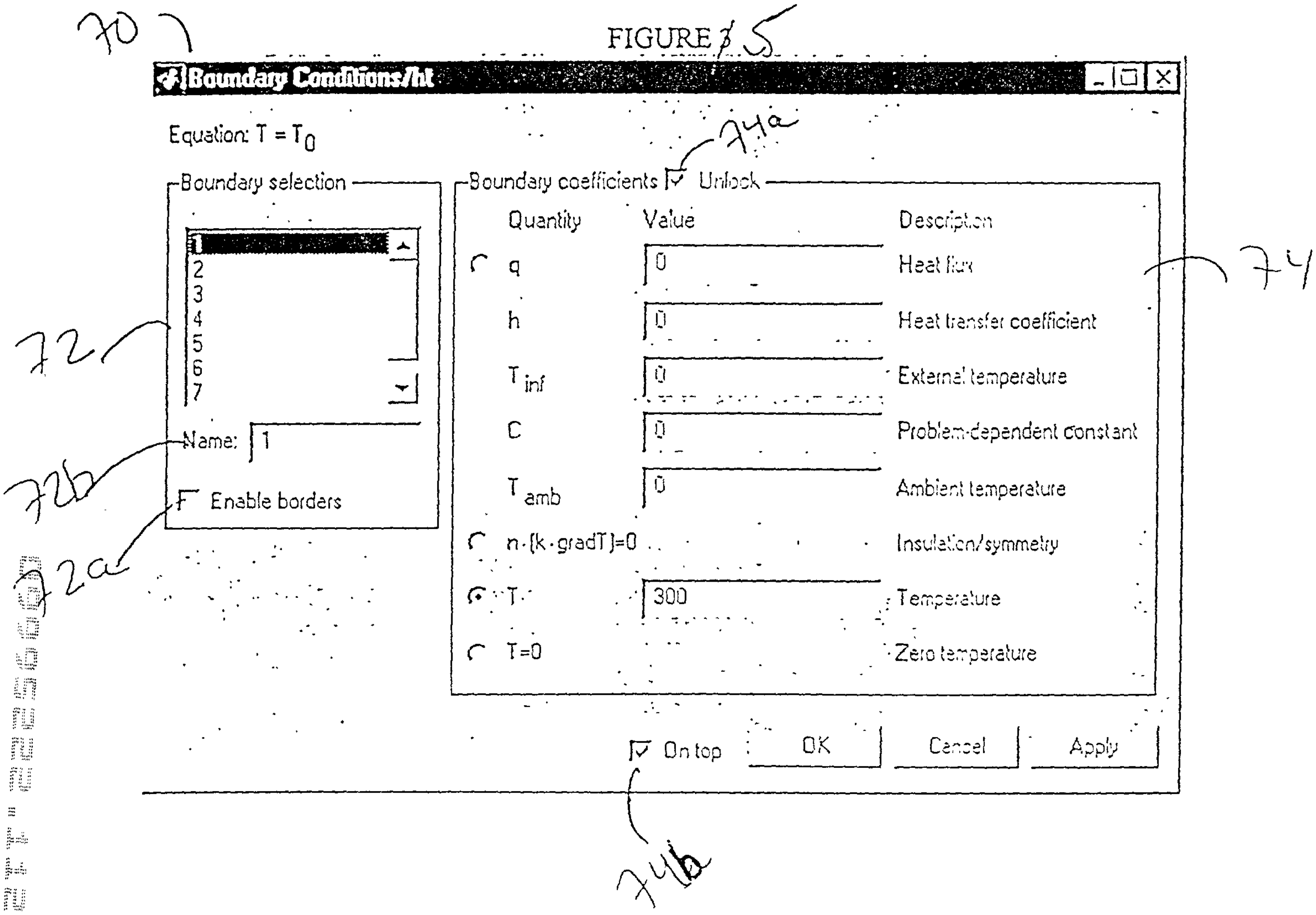
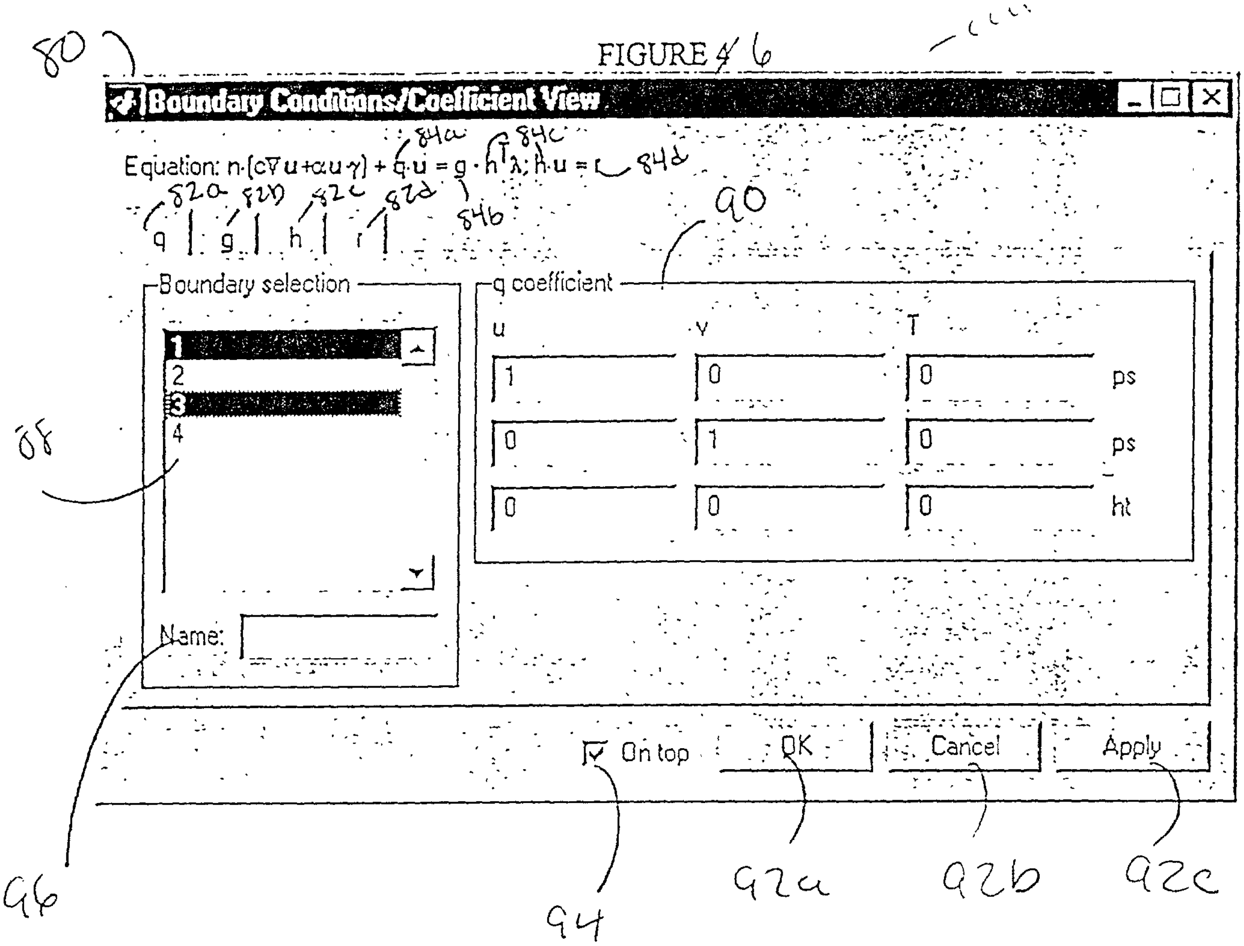

70
Boundary Conditions/ht
Equation: T = T0
Boundary selection
1
2
3
4
5
6
7
Name: 1
Enable borders
72
72b
72a
Boundary coefficients
Unlock
74a
Quantity
Value
Description
q
0
Heat flux
h
0
Heat transfer coefficient
T inf
0
External temperature
C
0
Problem-dependent constant
T amb
0
Ambient temperature
n·(k·gradT)=0
Insulation/symmetry
T
300
Temperature
T=0
Zero temperature
74
On top
74b
OK
Cancel
Apply

FIGURE ~~4~~ 6



80
Boundary Conditions/Coefficient View
Equation: n·(c∇u+αu-γ) + q·u = g - h^T λ; h·u = r
84a
84c
84d
82a
82b
82c
82d
84b
q
g
h
r
90
Boundary selection
1
2
3
4
Name:
q coefficient
u
v
T
1
0
0
ps
0
1
0
ps
0
0
0
ht
On top
OK
Cancel
Apply
88
96
94
92a
92b
92c

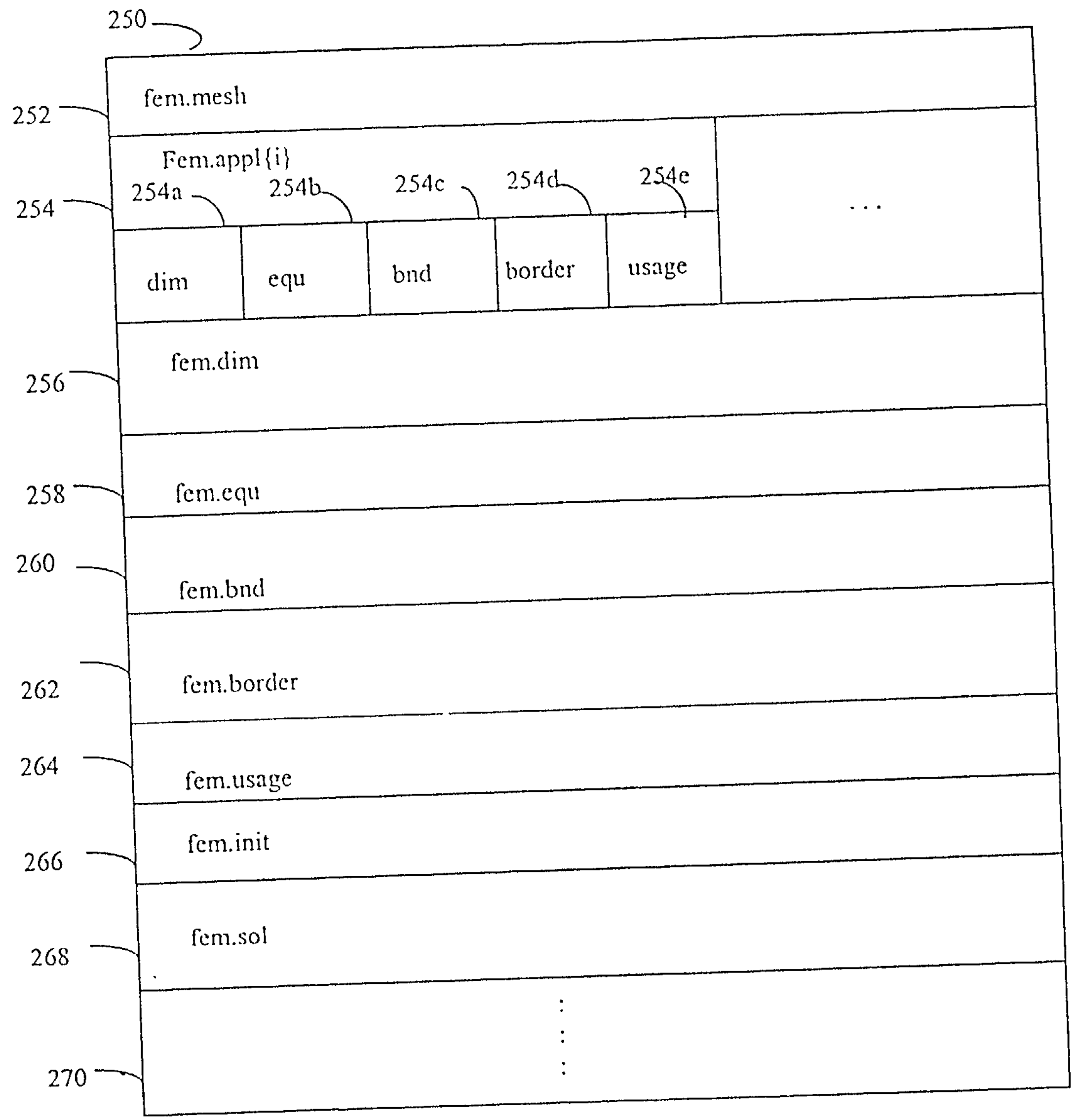
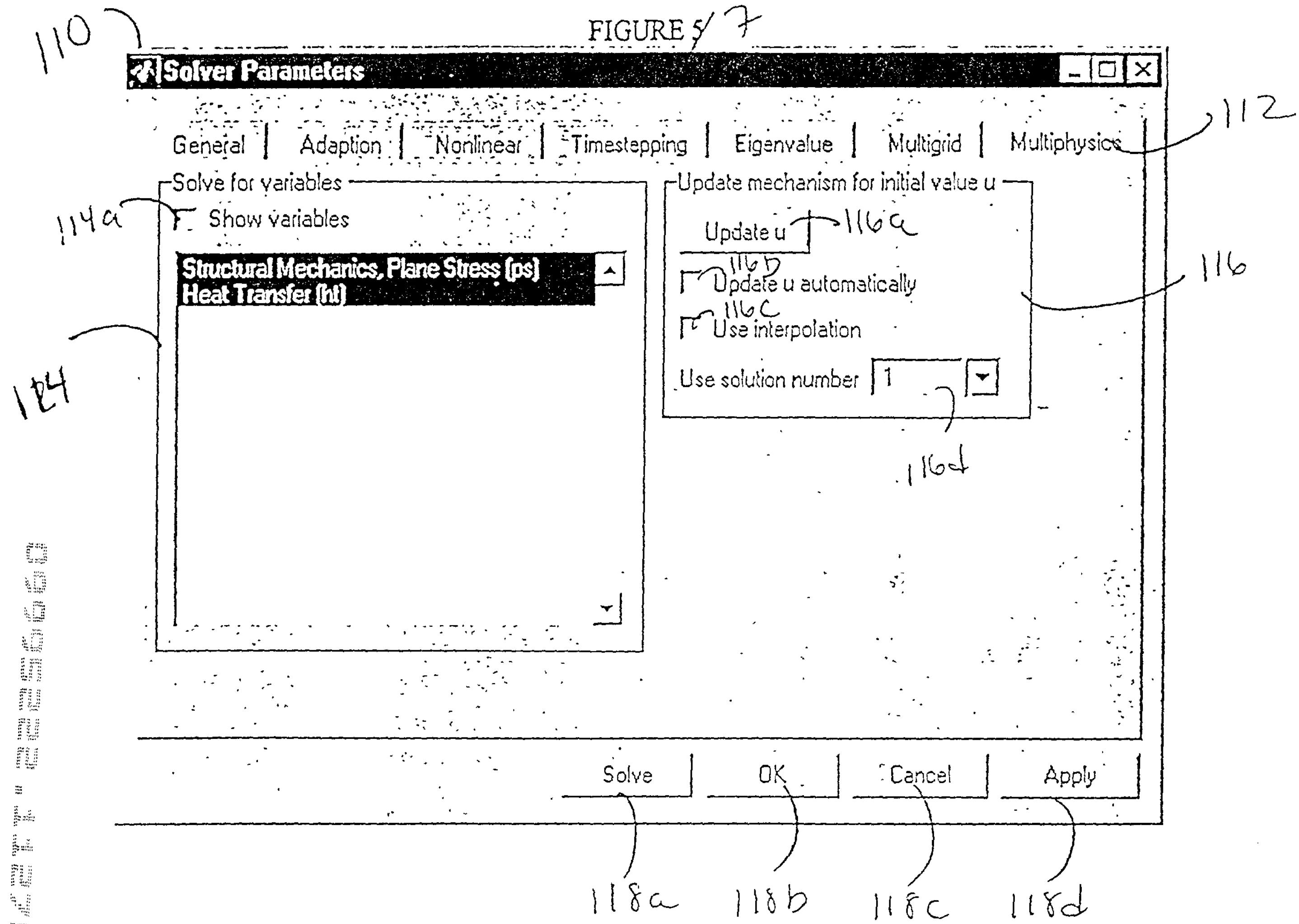

250
fem.mesh
252
Fem.appl{i}
254a
254b
254c
254d
254e
254
dim
equ
bnd
border
usage
. . .
fem.dim
256
fem.equ
258
fem.bnd
260
fem.border
262
fem.usage
264
fem.init
266
fem.sol
268
270

Figure 6A

FIGURE 5/7



Solver Parameters
General
Adaption
Nonlinear
Timestepping
Eigenvalue
Multigrid
Multiphysics
Solve for variables
Show variables
Structural Mechanics, Plane Stress (ps)
Heat Transfer (ht)
Update mechanism for initial value u
Update u
Update u automatically
Use interpolation
Use solution number
1
Solve
OK
Cancel
Apply
110
112
114a
116
116a
116b
116c
116d
124
118a
118b
118c
118d

FIGURE ~~6~~ 8

$$
140\left\{\begin{array}{ll}
d_{a\ lk}\dfrac{\partial u_k}{\partial t} - \dfrac{\partial}{\partial x_j}\left(c_{lkji}\dfrac{\partial u_k}{\partial x_i} + \alpha_{lkj}u_k - \gamma_{lj}\right) + \beta_{lki}\dfrac{\partial u_k}{\partial x_i} + a_{lk}u_k = f_l & \Omega \quad 142 \\
n_j\left(c_{lkji}\dfrac{\partial u_k}{\partial x_i} + \alpha_{lkj}u_k - \gamma_{lj}\right) + q_{lk}u_k = g_l - h_{ml}\lambda_m & \partial\Omega \quad 146a \\
h_{ml}u_l = r_m & \partial\Omega \quad 146b
\end{array}\right\} 146
$$

FIGURE ~~7~~ 9

$$
150\left\{\begin{array}{ll}
d_{a\ lk}\dfrac{\partial u_k}{\partial t} + \dfrac{\partial \Gamma_{lj}}{\partial x_j} = F_l & \Omega \quad 152 \\
-n_j\Gamma_{lj} = G_l + \dfrac{\partial R_m}{\partial u_l}\lambda_m & \partial\Omega \quad 154a \\
0 = R_m & \partial\Omega \quad 154b
\end{array}\right\} 154
$$

FIGURE 10

324

1

$$
\begin{cases}
\gamma_{Ij} = \Gamma_{Ij} & f_I = F_I \\
c_{IkjI} = -\dfrac{\partial \Gamma_{Ij}}{\partial\left(\dfrac{\partial u_k}{\partial x_i}\right)} & \alpha_{Ikj} = -\dfrac{\partial \Gamma_{Ij}}{\partial u_k} \\
\beta_{Iki} = -\dfrac{\partial F_I}{\partial\left(\dfrac{\partial u_k}{\partial x_i}\right)} & a_{Ik} = -\dfrac{\partial F_I}{\partial u_k} \\
g_I = G_I & r_I = R_I \\
q_{Ik} = -\dfrac{\partial G_I}{\partial u_k} & h_{Ik} = -\dfrac{\partial R_I}{\partial u_k}
\end{cases}
$$

FIGURE ~~9~~ 11

$$
240\left\{
\begin{aligned}
\Gamma_{lj} &= -c_{lkji}\frac{\partial u_k}{\partial x_i} - \alpha_{lkj}u_k + \gamma_{lj} \\
F_l &= f_l - \beta_{lki}\frac{\partial u_k}{\partial x_i} - a_{lk}u_k \\
G_l &= g_l - q_{lk}u_k \\
R_m &= r_m - h_{ml}u_l
\end{aligned}
\right.
$$

FIG 12

$$
\begin{cases}
\int_{\Omega}\left(\left(c_{lkji}\frac{\partial u_k}{\partial x_i} + \alpha_{lkj}u_k\right)\frac{\partial v}{\partial x_j} + \left(d_{a\,lk}\frac{\partial u_k}{\partial t} + \beta_{lki}\frac{\partial u_k}{\partial x_i} + a_{lk}u_k\right)v\right)dx + \\
\int_{\partial\Omega} q_{lk}u_k v\,ds = \int_{\Omega}\left(\gamma_{lj}\frac{\partial v}{\partial x_j} + f_l v\right)dx + \int_{\partial\Omega}(g_l - h_{ml}\lambda_m)v\,ds \\
\int_{\partial\Omega} \mu h_{mk}u_k\,ds = \int_{\partial\Omega} \mu r_m\,ds
\end{cases}
$$

FIG 13

$$302\left\{\begin{aligned}&\int_{\Omega}\left(\Gamma_{lj}\frac{\partial v}{\partial x_j}+F_l v-d_{alk}\frac{\partial u_k}{\partial t}v\right)dx+\int_{\partial\Omega}\left(G_l+\frac{\partial R_m}{\partial u_l}\lambda_m\right)v\,ds=0\\&\int_{\partial\Omega}R_m\,\mu\,ds=0\end{aligned}\right.$$

FIG 14

304

$$U_k(x) = \sum_{I=1}^{N_p} U_{I,k}\,\phi_I(x), \qquad \Lambda_m(x) = \sum_{K=1}^{N_e} \sum_{L=1}^{n} \Lambda_{K,L,m}\,\Psi_{K,L}(x)$$

FIG 15

206

$$
\begin{aligned}
&\int_{\tau}\left(c_{lkji}U_{I,k}\frac{\partial\phi_I}{\partial x_i}+\alpha_{lkj}U_{I,k}\phi_I\right)\frac{\partial\phi_J}{\partial x_j}\,dx+\\
&\int_{\tau}\left(d_{a\,lk}\frac{\partial U_{I,k}}{\partial t}\phi_I+\beta_{lki}U_{I,k}\frac{\partial\phi_I}{\partial x_i}+a_{lk}U_{I,k}\phi_I\right)\phi_J\,dx+\\
&\int_{\partial\tau}q_{lk}U_{I,k}\phi_I\phi_J\,ds=\int_{\tau}\left(\gamma_{lj}\frac{\partial\phi_J}{\partial x_j}+f_l\phi_J\right)dx+\\
&\int_{\partial\tau}(g_l-h_{m\,l}\Lambda_{K,L,m}\Psi_{K,L})\phi_J\,ds
\end{aligned}
$$

FIG 16

308

$$\int_{\partial\tau} h_{mk} U_{I,k} \phi_I \Psi_{K,L}\, ds = \int_{\partial\tau} r_m \Psi_{K,L}\, ds$$

FIG 17

312

$$\begin{cases} \int_{\tau}\left(\Gamma_{Ij}\dfrac{\partial\phi_J}{\partial x_j}+F_I\phi_J-d_{aIk}\dfrac{\partial u_k}{\partial t}\phi_J\right)dx+\int_{\partial\tau}\left(G_I+\dfrac{\partial R_m}{\partial u_I}\Lambda_{K,L,m}\Psi_{K,L}\right)\phi_J ds=0 \\ \int_{\partial\tau}R_m\Psi_{K,L}ds=0 \end{cases}$$

FIG 18

310

$$DA_{(J,I),(I,k)} = \int_{\tau} d_{a\,Ik} \phi_I \phi_J \, dx$$

$$C_{(J,I),(I,k)} = \int_{\tau} c_{Ikji} \frac{\partial \phi_I}{\partial x_i} ? \frac{\partial \phi_J}{\partial x_j} \, dx$$

$$AL_{(J,I),(I,k)} = \int_{\tau} \alpha_{Ikj} \phi_I ? \frac{\partial \phi_J}{\partial x_j} \, dx$$

$$BE_{(J,I),(I,k)} = \int_{\tau} \beta_{Iki} \frac{\partial \phi_I}{\partial x_i} \phi_J \, dx$$

$$A_{(J,I),(I,k)} = \int_{\tau} a_{Ik} \phi_I \phi_J \, dx$$

$$Q_{(J,I),(I,k)} = \int_{\partial\tau} q_{Ik} \phi_I \phi_J \, ds$$

$$GA_{(J,I)} = \int_{\tau} \gamma_{Ij} \frac{\partial \phi_J}{\partial x_j} \, dx$$

$$F_{(J,I)} = \int_{\tau} f_I \phi_J \, dx$$

$$G_{(J,I)} = \int_{\partial\tau} g_I \phi_J \, ds$$

$$H_{(K,L,m),(I,k)} = \int_{\partial\tau} h_{mk} \phi_I \Psi_{K,L} \, ds$$

$$R_{(K,L,m)} = \int_{\partial\tau} r_m \Psi_{K,L} \, ds$$

FIG 19

$$\begin{cases} DA\frac{\partial U}{\partial t} + (C + AL + BE + A + Q)U + H^T\Lambda = GA + F + G \\ HU = R \end{cases}$$

FIG 20

$$\begin{cases} DA\dfrac{\partial U}{\partial t} + H^T\Lambda = GA + F + G \\ R = 0 \end{cases}$$

FIG 21

$$326\left\{\begin{array}{l} J(U^{(k)})\Delta U^{(k)} = -\rho(U^{(k)}) \\ U^{(k+1)} = U^{(k)} + \lambda_k \Delta U^{(k)} \end{array}\right.$$

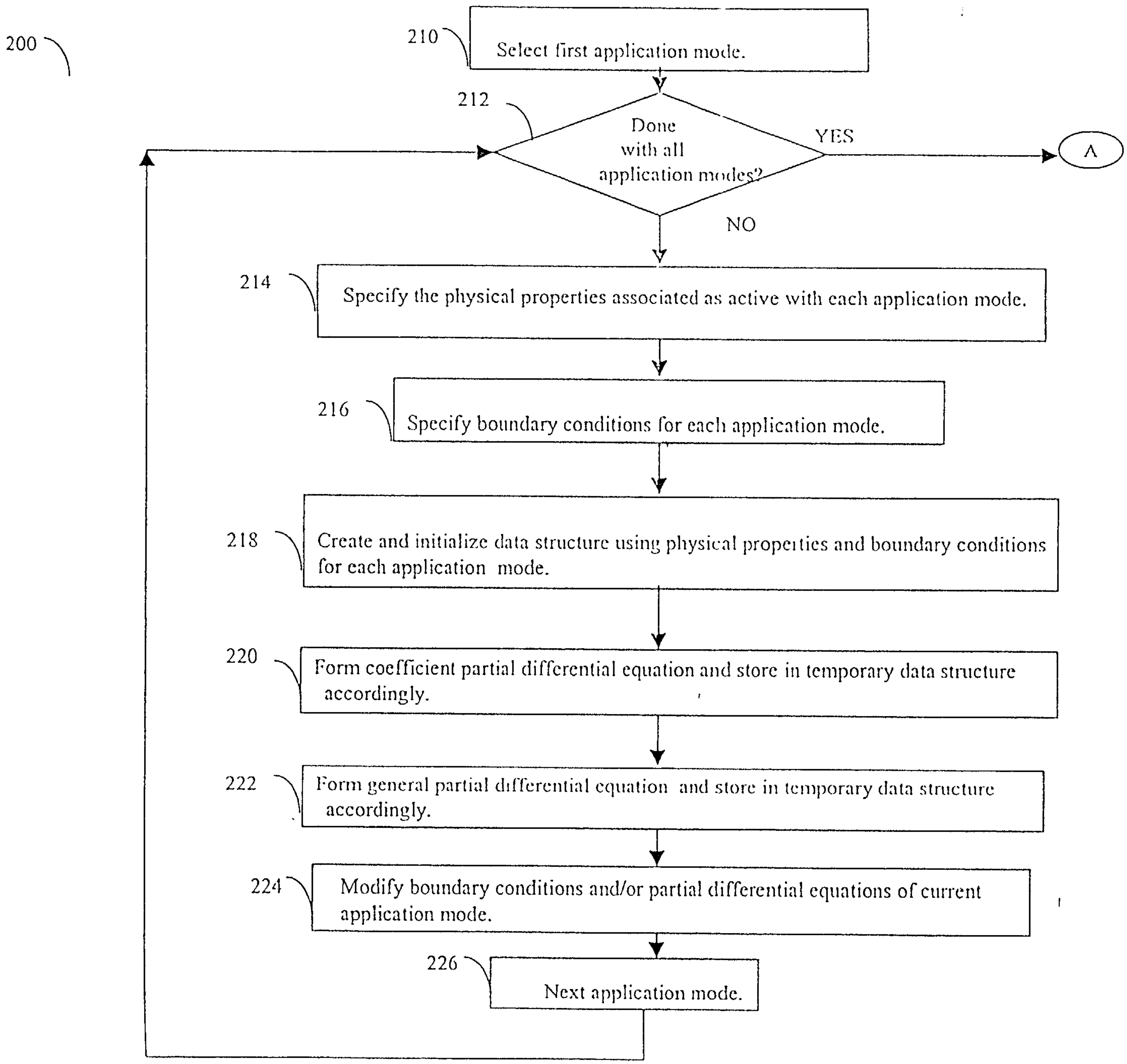

200
210
Select first application mode.
212
Done
with all
application modes?
YES
A
NO
214
Specify the physical properties associated as active with each application mode.
216
Specify boundary conditions for each application mode.
218
Create and initialize data structure using physical properties and boundary conditions for each application mode.
220
Form coefficient partial differential equation and store in temporary data structure accordingly.
222
Form general partial differential equation and store in temporary data structure accordingly.
224
Modify boundary conditions and/or partial differential equations of current application mode.
226
Next application mode.

Figure 22

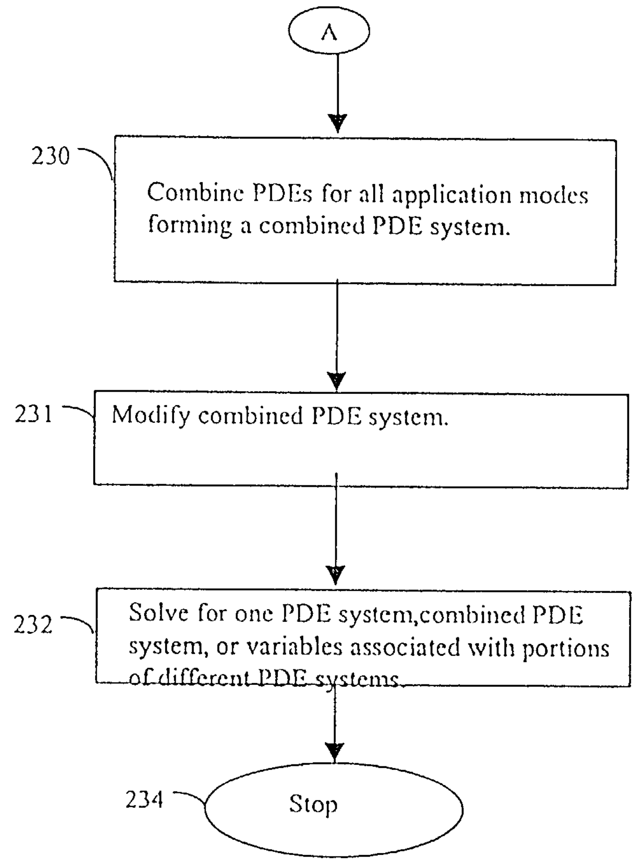
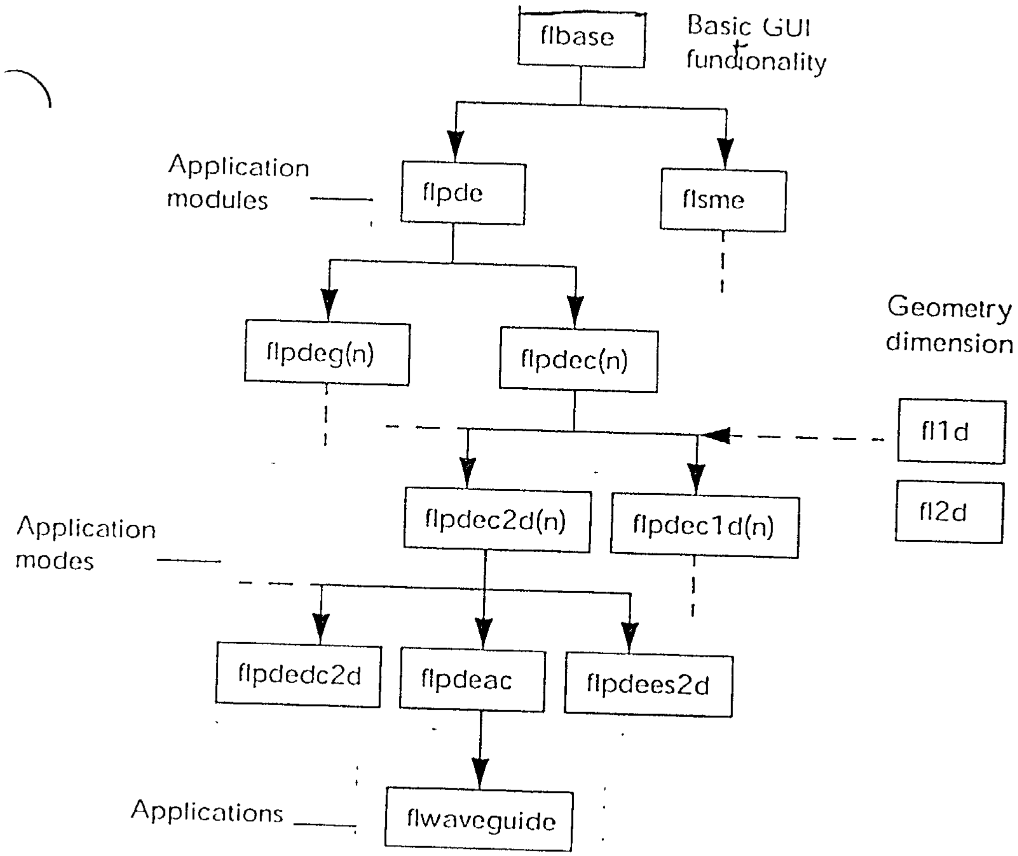

A
230
Combine PDEs for all application modes forming a combined PDE system.
231
Modify combined PDE system.
232
Solve for one PDE system,combined PDE system, or variables associated with portions of different PDE systems.
234
Stop

FIGURE 23

500



The class hierarchy of FEMLAB

FIGURE 24

1-D Physics Application Modes

Application mode	Class name	Parent class
Diffusion	`flpdedf1d`	`flpdedf`
Heat Transfer	`flpdeht1d`	`flpdeht`

502

: **1-D PDE Application Modes**

Application mode	Class name	Parent class
Coefficient PDE model, n variables	`flpdec1d`*(n)*	`flpdec`*(n)*
General PDE model, n variables	`flpdeg1d`*(n)*	`flpdeg`*(n)*

504

FIGURE 25

FIGURE 26

2-D Physics Application Modes

Application mode	Class name	Parent class
AC Power Electromagnetics	flpdeac	flpdec2d
Conductive Media DC	flpdedc2d	flpdedc
Diffusion	flpdedf2d	flpdedf
Electrostatics	flpdees2d	flpdees
Magnetostatics	flpdems2d	flpdems
Heat Transfer	flpdeht2d	flpdeht
Incompressible Navier-Stokes	flpdens2d	flpdens
Structural Mechanics, Plane Stress	flpdeps	flpdec2d
Structural Mechanics, Plane Strain	flpdepn	flpdec2d

506

PDE Application Modes

Application mode	Class name	Parent class
Coefficient PDE model, n variables	flpdec2d *(n)*	flpdec *(n)*
General PDE model, n variables	flpdeg2d *(n)*	flpdeg *(n)*

508

FIGURE 27

Application Object Properties

Property name	Description	Data type
`dim`	Names of the dependent variables	Cell array of strings
`form`	PDE form	String (`coefficient`/`general`)
`name`	Application name	String
`parent`	Parent class names	String, cell array of strings, or the empty matrix
`sdim`	Names of the independent variables (space dimensions)	Cell array of strings
`submode`	Name of current submode	String (`std`/`wave`)
`tdiff`	Time differentiation flag	String (`on`/`off`)

510

512

```
function obj = myapp()
%MYAPP Constructor for a FEMLAB application object.

obj.name = 'My first FEMLAB application';
obj.parent = 'flpdeht2d';

% MYAPP is a subclass of FLPDEHT2D:
p1 = flpdeht2d;
obj = class(obj,'myapp',p1);
set(obj,'dim',default_dim(obj));
```

FIGURE 28

Physics Modeling Methods

514

Function	Purpose
appspec	Return application specifications.
bnd_compute	Convert application-dependent boundary conditions to generic boundary coefficients.
default_bnd	Default boundary conditions.
default_dim	Default names of dependent variables.
default_equ	Default PDE coefficients/Material parameters.
default_init	Default initial conditions.
default_sdim	Default space dimension variables.
default_var	Default application scalar variables.
dim_compute	Return dependent variables for an application.
equ_compute	Convert application-dependent material parameters to generic PDE coefficients.
form_compute	Return PDE form.
init_compute	Convert application-dependent initial conditions to generic initial conditions.
posttable	Define assigned variable names and post-processing information.

FIGURE 29

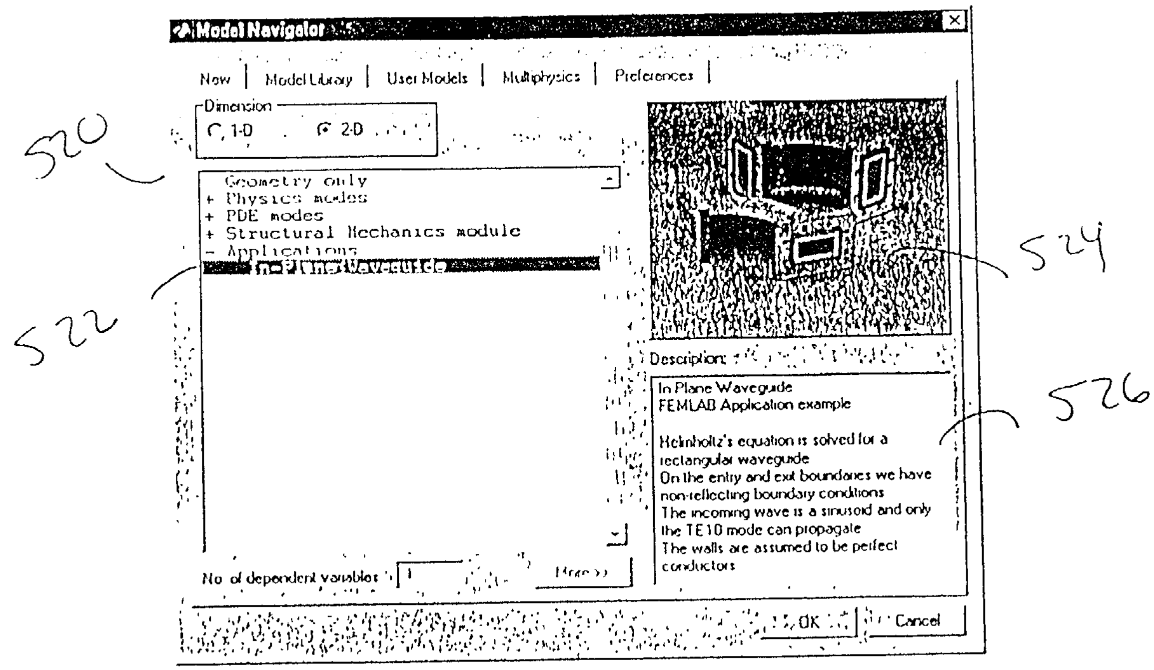

Model Navigator
New
Model Library
User Models
Multiphysics
Preferences
Dimension
1-D
2-D
Geometry only
+ Physics modes
+ PDE modes
+ Structural Mechanics module
- Applications
In-Plane Waveguide
Description:
In Plane Waveguide
FEMLAB Application example
Helmholtz's equation is solved for a rectangular waveguide
On the entry and exit boundaries we have non-reflecting boundary conditions
The incoming wave is a sinusoid and only the TE10 mode can propagate
The walls are assumed to be perfect conductors
No of dependent variables
1
OK
Cancel
520
522
524
526

FIGURE 30

530 $$\Delta E_z + (2\pi i k)^2 E_z = 0$$

532 $$k = \frac{1}{\lambda} = \frac{f}{c}$$

534 $$\bar{n} \cdot (\nabla E_z) + 2\pi i k_x E_z = 4\pi i k_x \sin\left(\frac{\pi}{d}(y - y_0)\right)$$

536 $$k^2 = k_x^2 + k_y^2$$

538 $$k_x = \sqrt{\frac{1}{\lambda^2} - \frac{1}{(2d)^2}}$$

540 $$n \cdot (\nabla E_z) + 2\pi i k_x E_z = 0$$

542 $$E_z = 0$$

544 $$f_c = \frac{c}{2d}$$

FIGURE 31

550

```
function obj = flwaveguide(varargin)
%FLWAVEGUIDE Constructor for a Waveguide application object.

obj.name = 'In-Plane Waveguide';
obj.parent = 'flpdeac';

% FLWAVEGUIDE is a subclass of FLPDEAC:
p1 = flpdeac;
obj = class(obj,'flwaveguide',p1);
set(obj,'dim',default_dim(obj));
```

FIGURE 32

552

fem.user fields

Field	Description
geomparam	1-by-2 structure of geometry parameters.
entrybnd	Index to the entry boundary.
exitbnd	Index to the exit boundary.
freqs	Frequency vector

FIGURE 33

554

fem.user fields

Field	Description
startpt	Index of the lower left corner point of the waveguide.
type	Type of waveguide. ('*straight* or '*elbow*)

FIGURE 34

556

geomparam fields

Field	Description	Defaults for elbow	Defaults for straight
entrylength	Length of the entrance part of the waveguide.	0.1	0.1
exitlength	Length of the exit part of the waveguide.	0.1	Not used
radius	Outer radius of the waveguide bend.	0.05	Not used
width	Width of the waveguide.	0.025	0.025
cavityflag	Turn resonance cavity *on* or *off*.	0	0
cavitywidth	Width of the resonance cavity.	0.025	0.025
postwidth	Width of the protruding posts.	0.005	0.005
postdepth	Depth of the protruding posts.	0.005	0.005

FIGURE 35

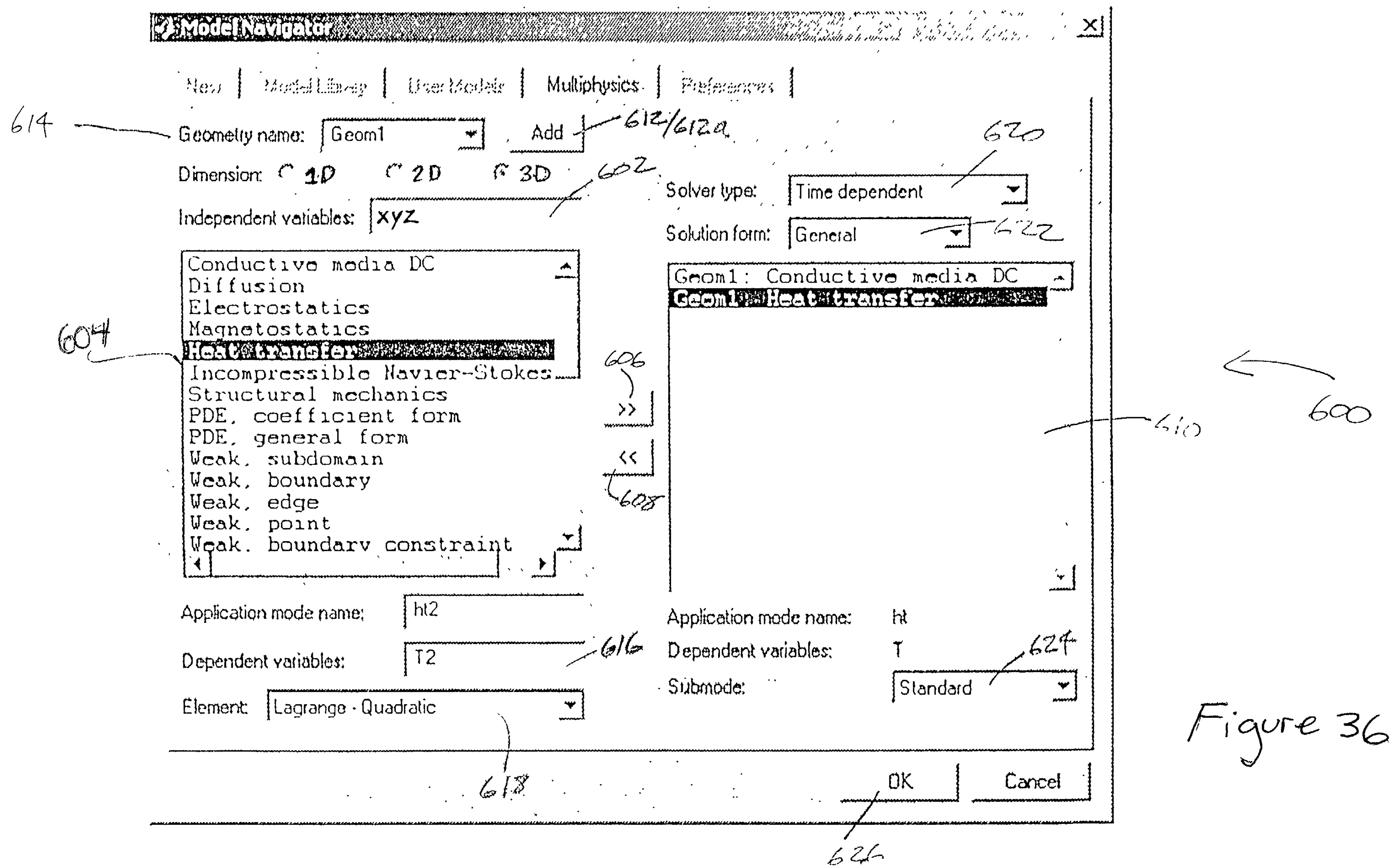

Model Navigator
New
Model Library
User Models
Multiphysics
Preferences
Geometry name:
Geom1
Add
Dimension: 1D 2D 3D
Independent variables:
xyz
Conductive media DC
Diffusion
Electrostatics
Magnetostatics
Heat transfer
Incompressible Navier-Stokes
Structural mechanics
PDE, coefficient form
PDE, general form
Weak, subdomain
Weak, boundary
Weak, edge
Weak, point
Weak, boundary constraint
>>
<<
Solver type:
Time dependent
Solution form:
General
Geom1: Conductive media DC
Geom1: Heat transfer
Application mode name:
ht2
Dependent variables:
T2
Element:
Lagrange - Quadratic
Application mode name:
ht
Dependent variables:
T
Submode:
Standard
OK
Cancel
614
612/612a
620
602
622
604
606
608
610
600
616
624
618
626

Figure 36

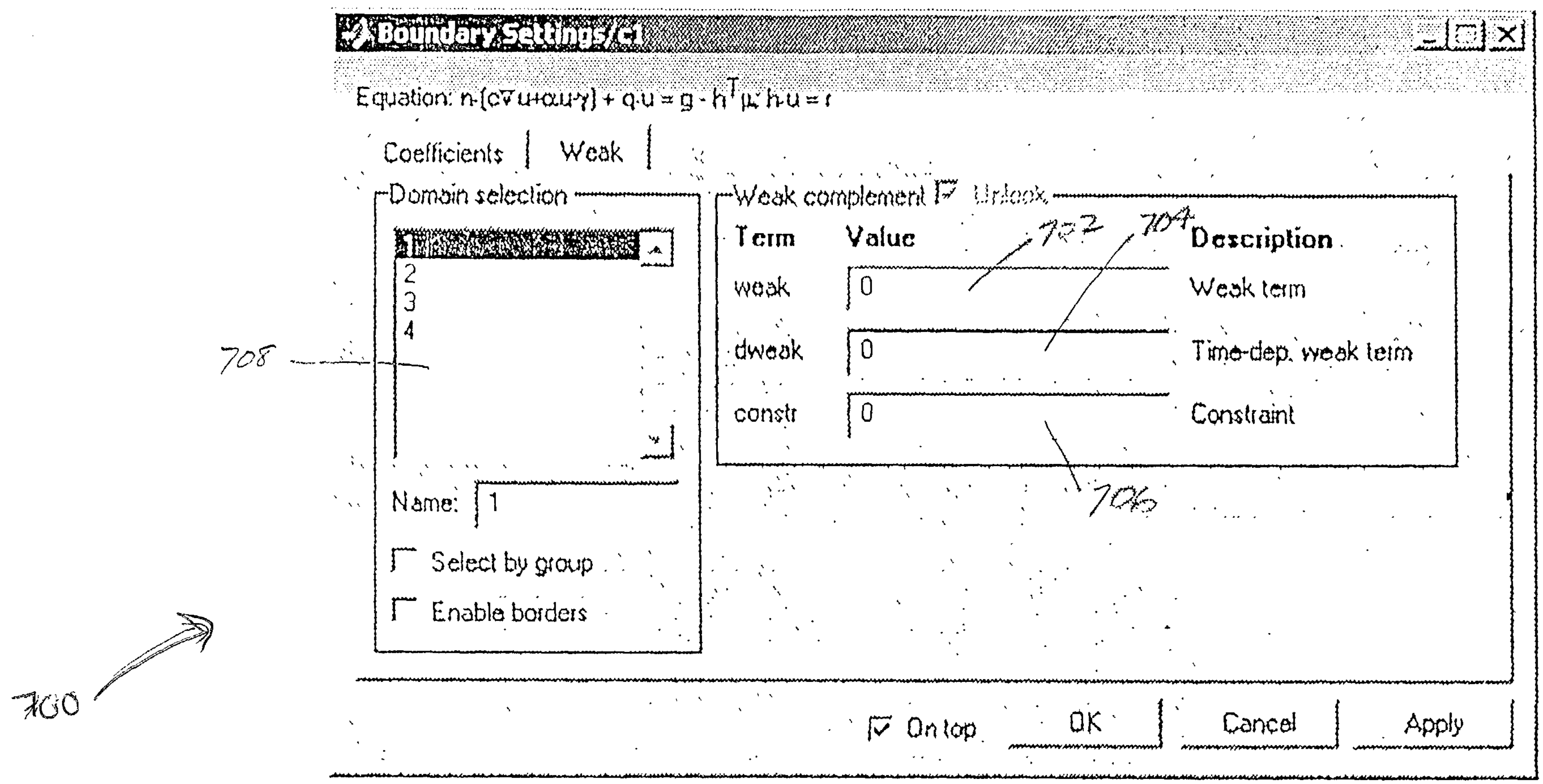

Boundary Settings/c1
Equation: n·(c∇u+αu-γ) + q·u = g - h^T μ; h·u = r
Coefficients
Weak
Domain selection
1
2
3
4
Name: 1
Select by group
Enable borders
Weak complement
Unlock
Term
Value
Description
weak
0
Weak term
dweak
0
Time-dep. weak term
constr
0
Constraint
On top
OK
Cancel
Apply
700
702
704
706
708

Figure 37

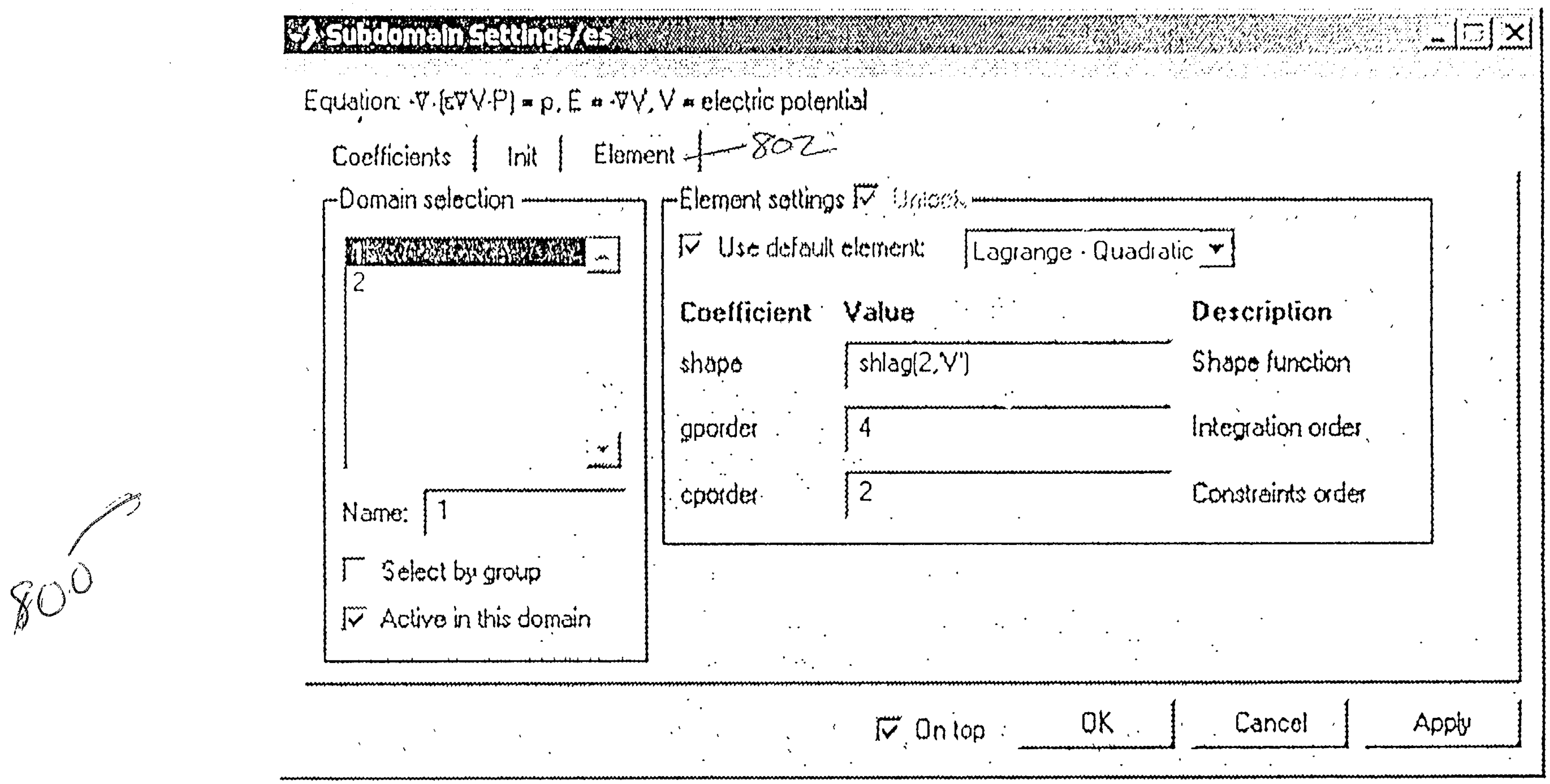
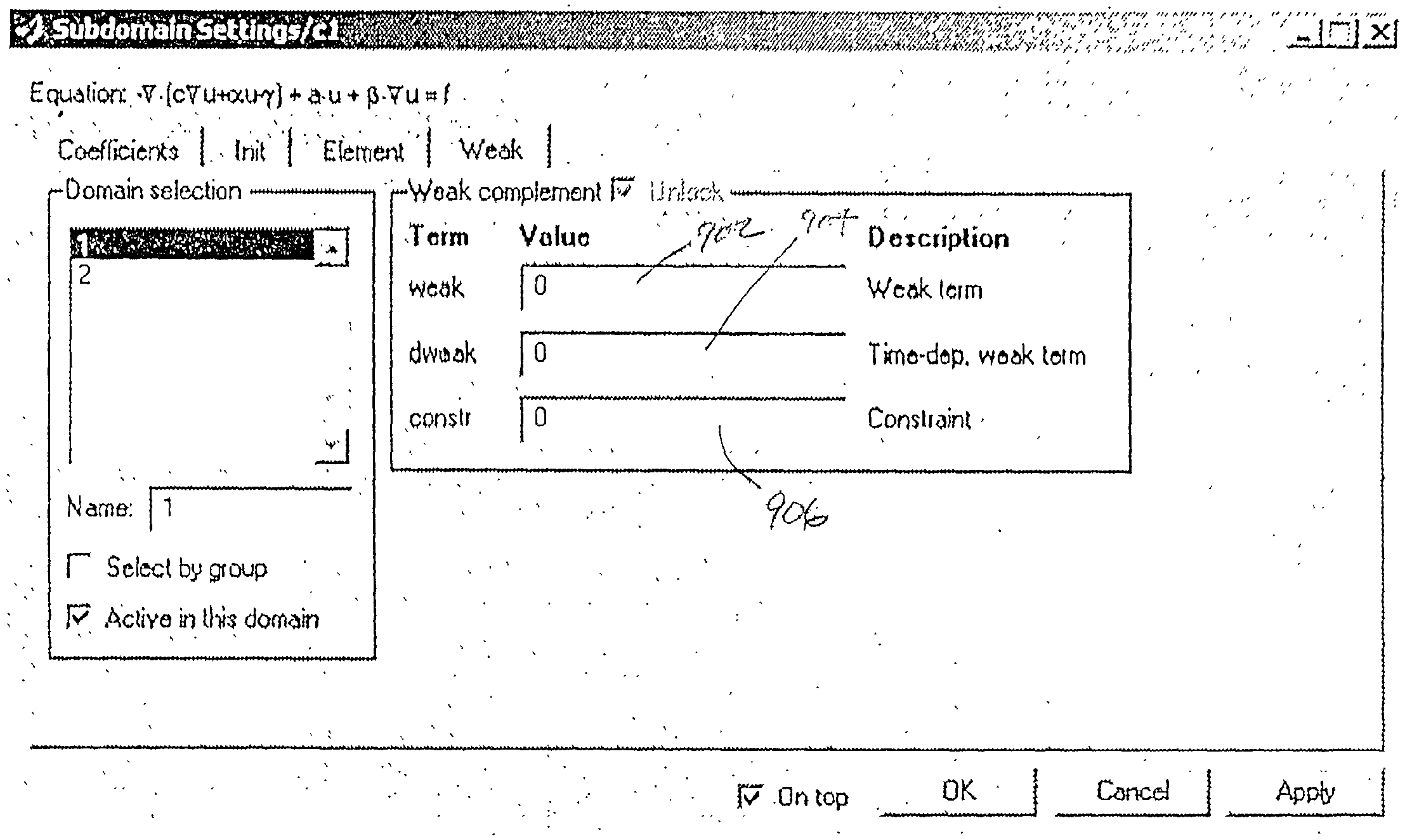

Subdomain Settings/es
Equation: -∇·(ε∇V-P) = ρ, E = -∇V, V = electric potential
Coefficients
Init
Element
802
Domain selection
2
Name: 1
Select by group
Active in this domain
Element settings
Use default element:
Lagrange - Quadratic
Coefficient
Value
Description
shape
shlag(2,'V')
Shape function
gporder
4
Integration order
cporder
2
Constraints order
On top
OK
Cancel
Apply
800

Figure 38



↑ 900

Figure 39

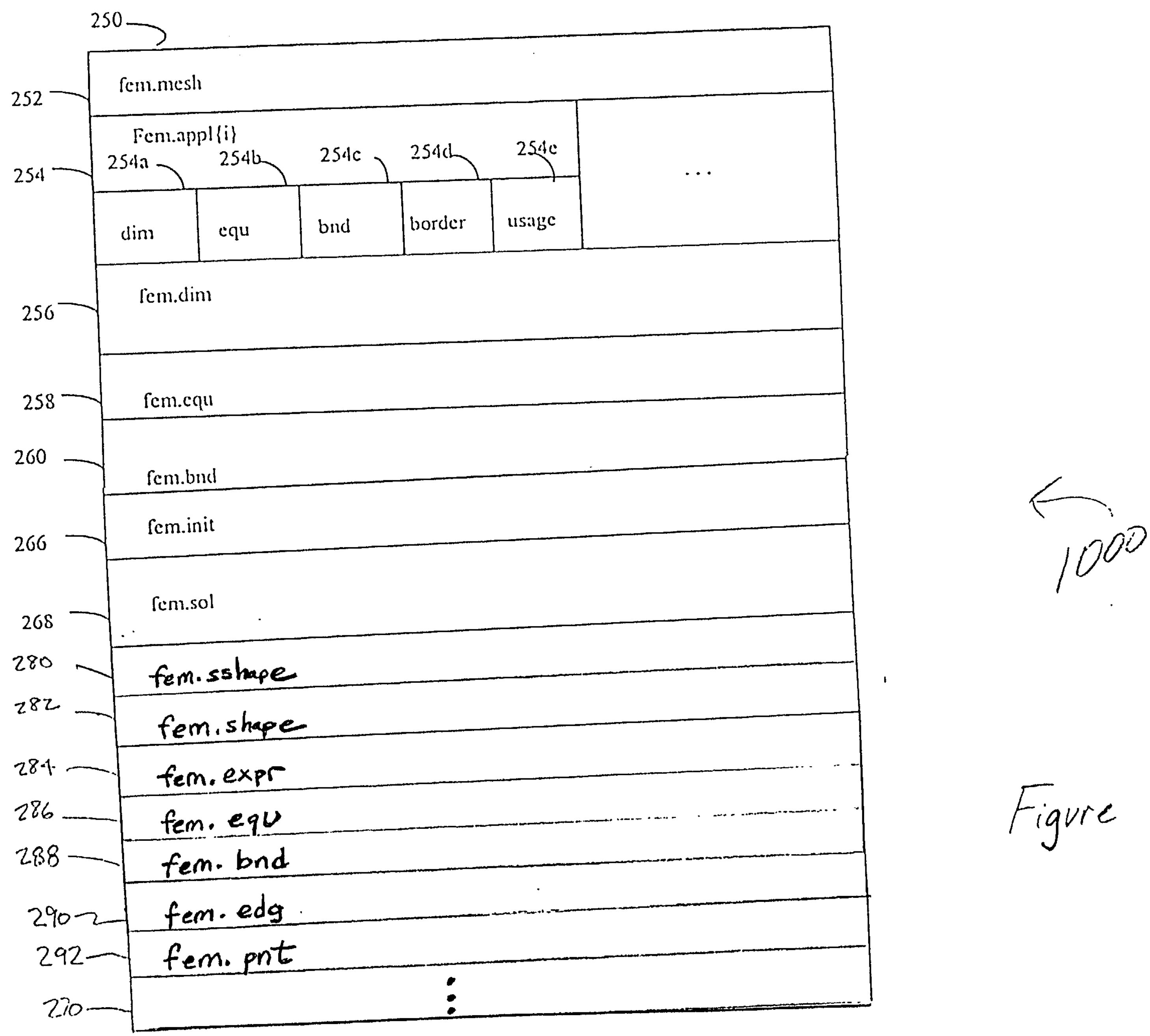

250
fem.mesh
252
Fem.appl{i}
254
254a
254b
254c
254d
254e
dim
equ
bnd
border
usage
...
fem.dim
256
fem.equ
258
fem.bnd
260
fem.init
266
fem.sol
268
fem.sshape
280
fem.shape
282
fem.expr
284
fem.equ
286
fem.bnd
288
fem.edg
290
fem.pnt
292
220
1000

Figure 40

1102

$$
\left\{
\begin{aligned}
0 &= \int_{\Omega} W^{(2)} dA + \int_{B} W^{(1)} ds + \sum_{P} W^{(0)} + \\
&+ \int_{\Omega} v_l \frac{\partial R_m^{(2)}}{\partial u_l} \mu_m^{(2)} dA + \int_{B} v_l \frac{\partial R_m^{(1)}}{\partial u_l} \mu_m^{(1)} ds + \sum_{P} v_l \frac{\partial R_m^{(0)}}{\partial u_l} \mu_m^{(0)}
\end{aligned}
\right.
$$

1104

$$
\left\{
\begin{aligned}
0 &= R^{(2)} \quad \text{on } \Omega \\
0 &= R^{(1)} \quad \text{on B} \\
0 &= R^{(0)} \quad \text{on P}
\end{aligned}
\right.
$$

1100

Figure 41

$$W_l^{(n)} = W_l^{(n)} + \Gamma_{lj}\frac{\partial v_l}{\partial x_j} + F_l v_l$$

$$W_l^{(nt)} = W_l^{(nt)} + d_{alk}\frac{\partial u_k}{\partial t} v_l$$

$$W_l^{(n-1)} = W_l^{(n-1)} + G_l v_l$$

$$R_m^{(n)} = R_m$$

1200

Figure 42

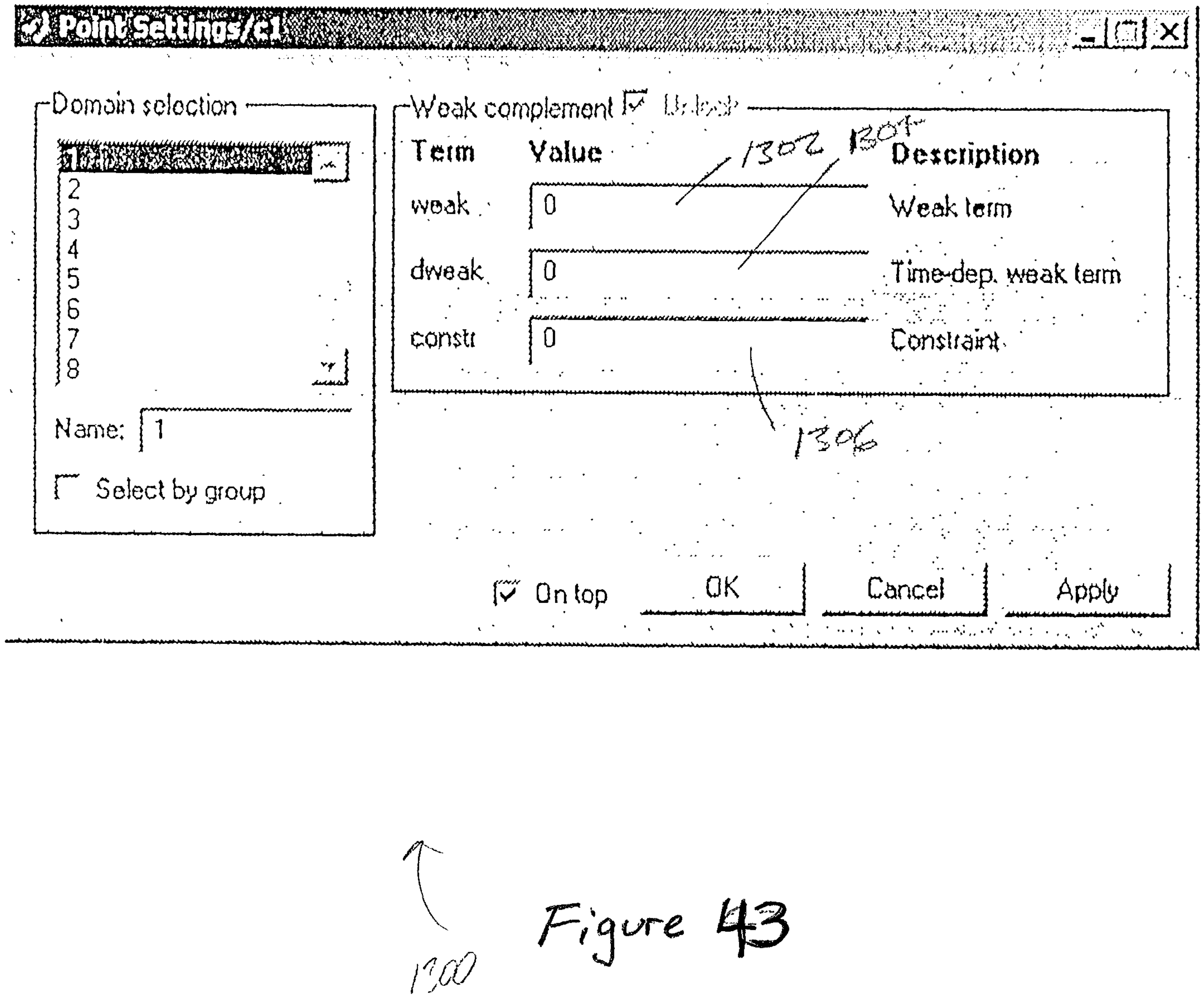
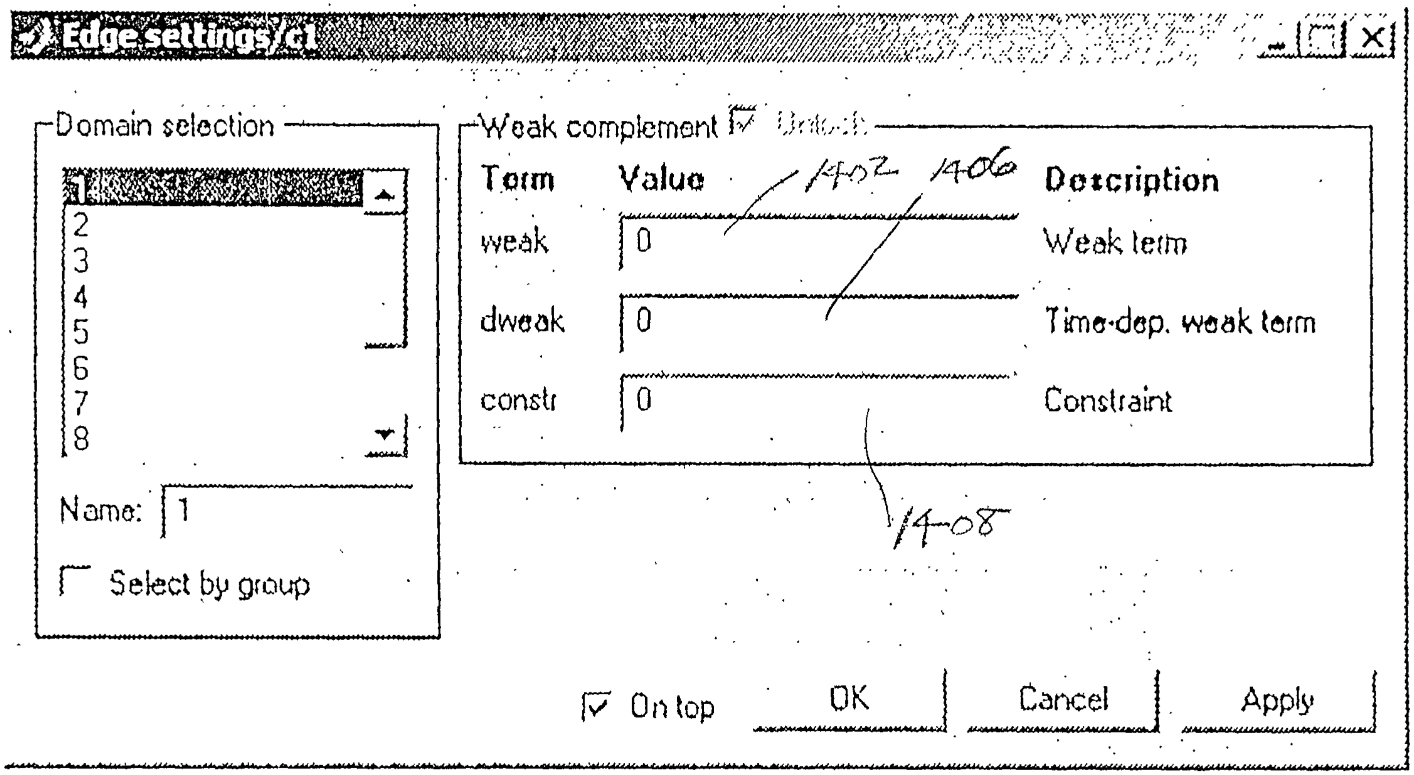

Point Settings/c1
Domain selection
1
2
3
4
5
6
7
8
Name: 1
Select by group
Weak complement
Unlock
Term
Value
Description
weak
0
Weak term
dweak
0
Time-dep. weak term
constr
0
Constraint
1302
1304
1306
On top
OK
Cancel
Apply
1300

Figure 43



1400

Figure 44

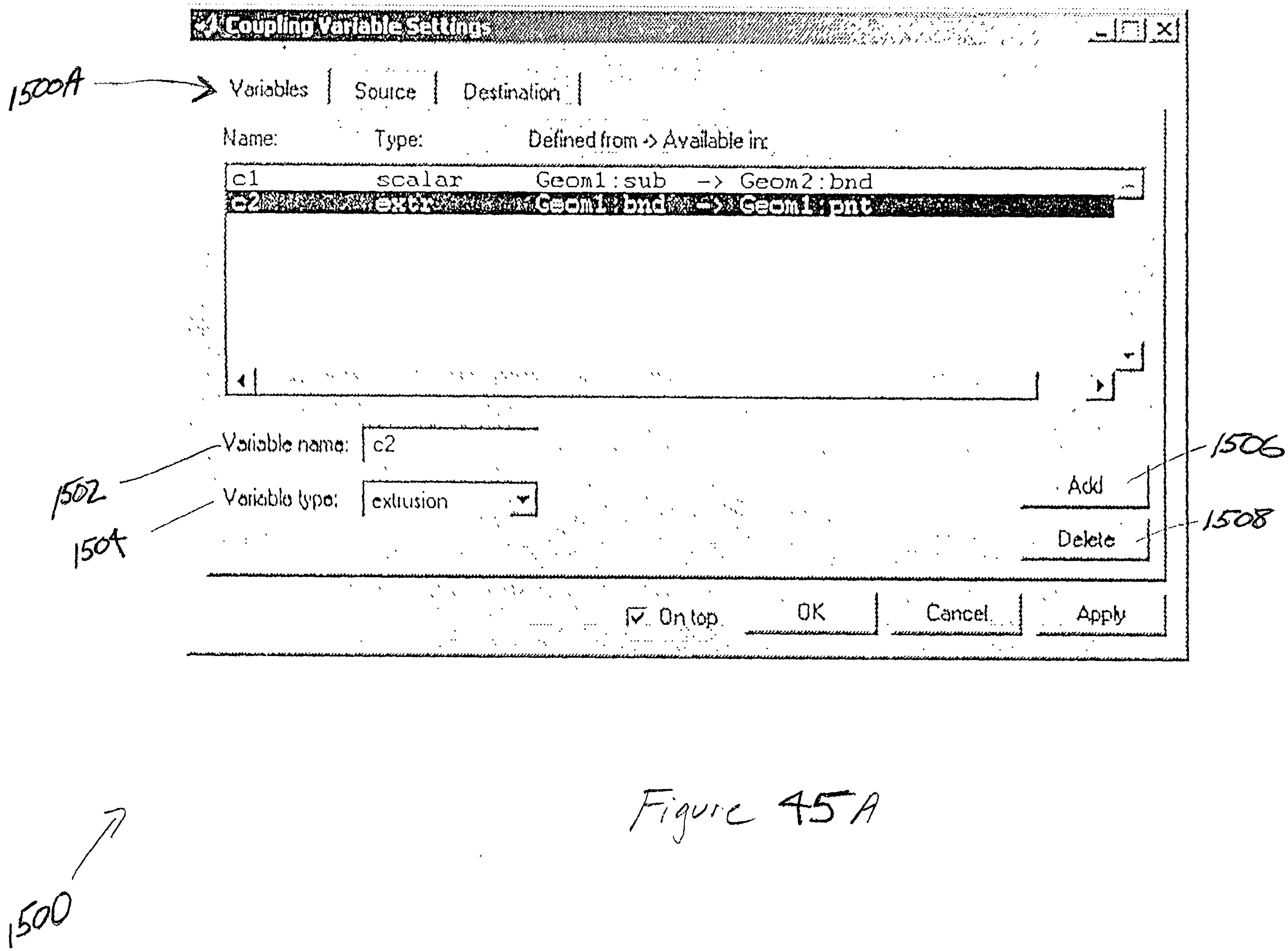

Coupling Variable Settings
Variables
Source
Destination
Name:
Type:
Defined from -> Available in:
c1 scalar Geom1:sub -> Geom2:bnd
c2 extr Geom1:bnd -> Geom1:pnt
Variable name:
c2
Variable type:
extrusion
Add
Delete
On top
OK
Cancel
Apply
1500A
1502
1504
1506
1508
1500

Figure 45A

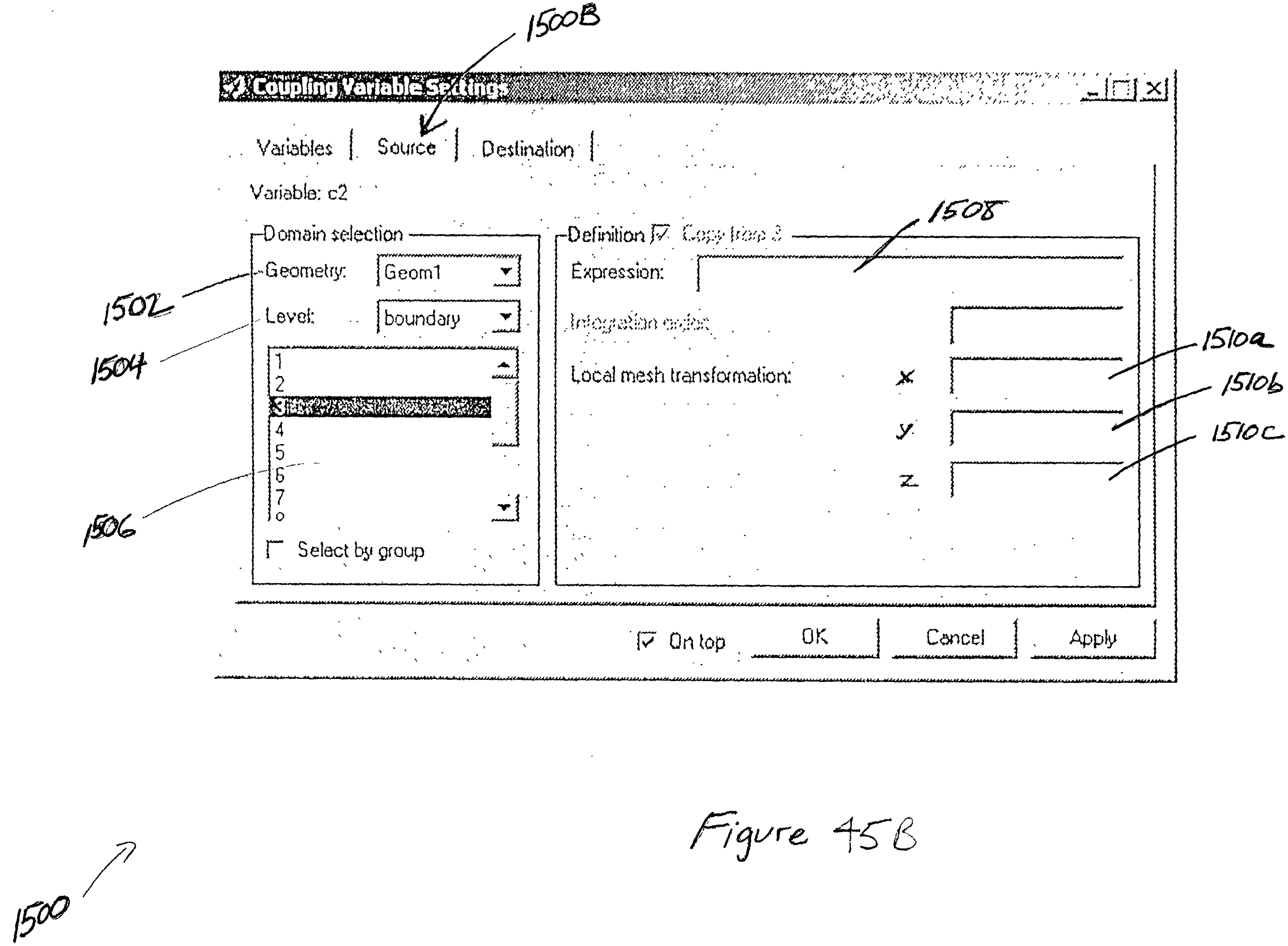

1500B
Coupling Variable Settings
Variables
Source
Destination
Variable: c2
Domain selection
Geometry:
Geom1
Level:
boundary
1
2
3
4
5
6
7
Select by group
Definition
Expression:
Integration order:
Local mesh transformation:
x
y
z
On top
OK
Cancel
Apply
1502
1504
1506
1508
1510a
1510b
1510c
1500

Figure 45B

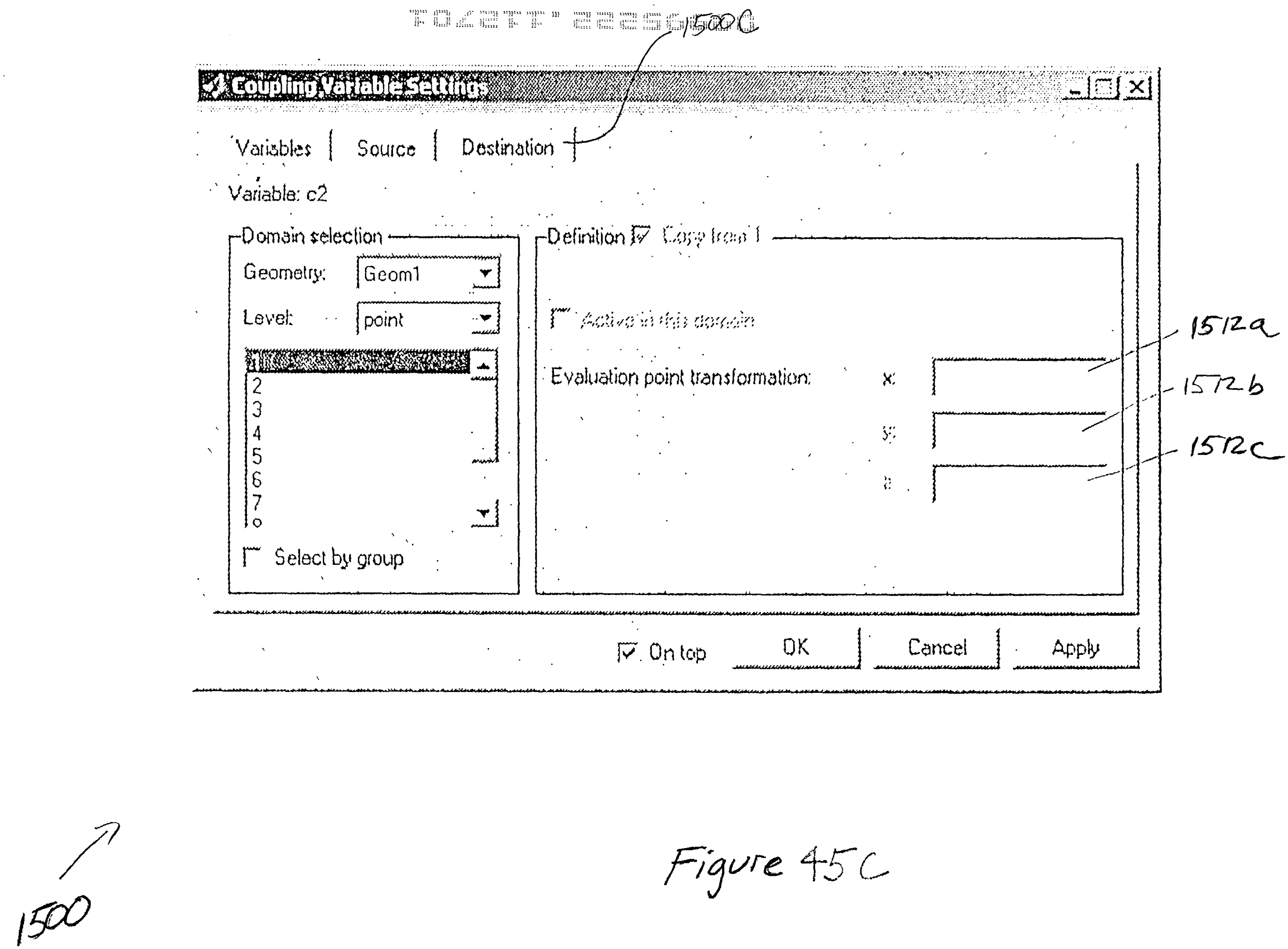

1500C
Coupling Variable Settings
Variables
Source
Destination
Variable: c2
Domain selection
Geometry:
Geom1
Level:
point
1
2
3
4
5
6
7
Select by group
Definition
Copy from 1
Active in this domain
Evaluation point transformation:
x:
y:
z:
1512a
1512b
1512c
On top
OK
Cancel
Apply
1500

Figure 45C

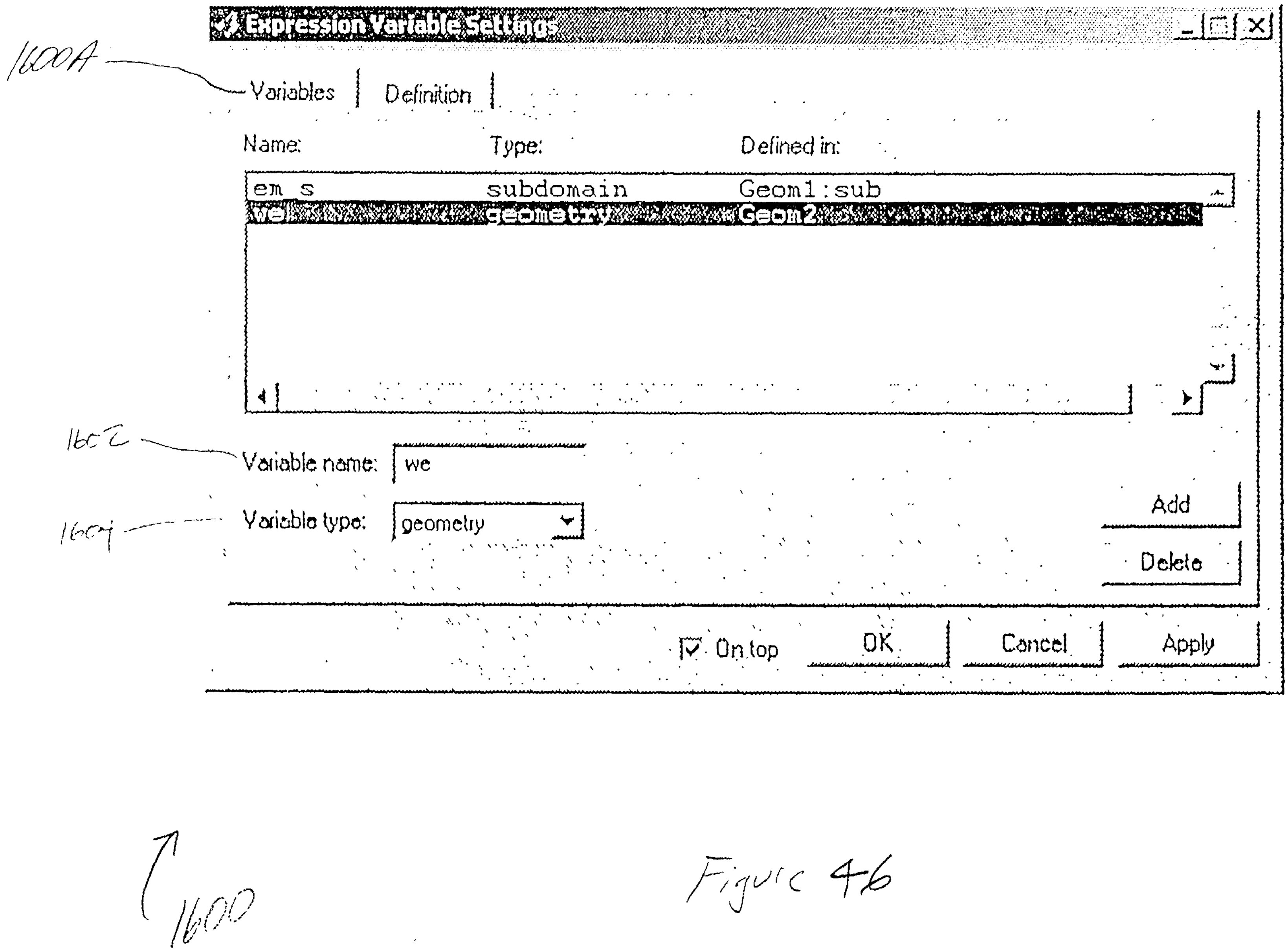

Expression Variable Settings
Variables
Definition
Name:
Type:
Defined in:
em_s
subdomain
Geom1:sub
we
geometry
Geom2
Variable name:
we
Variable type:
geometry
Add
Delete
On top
OK
Cancel
Apply
1600A
1602
1604
1600

Figure 46

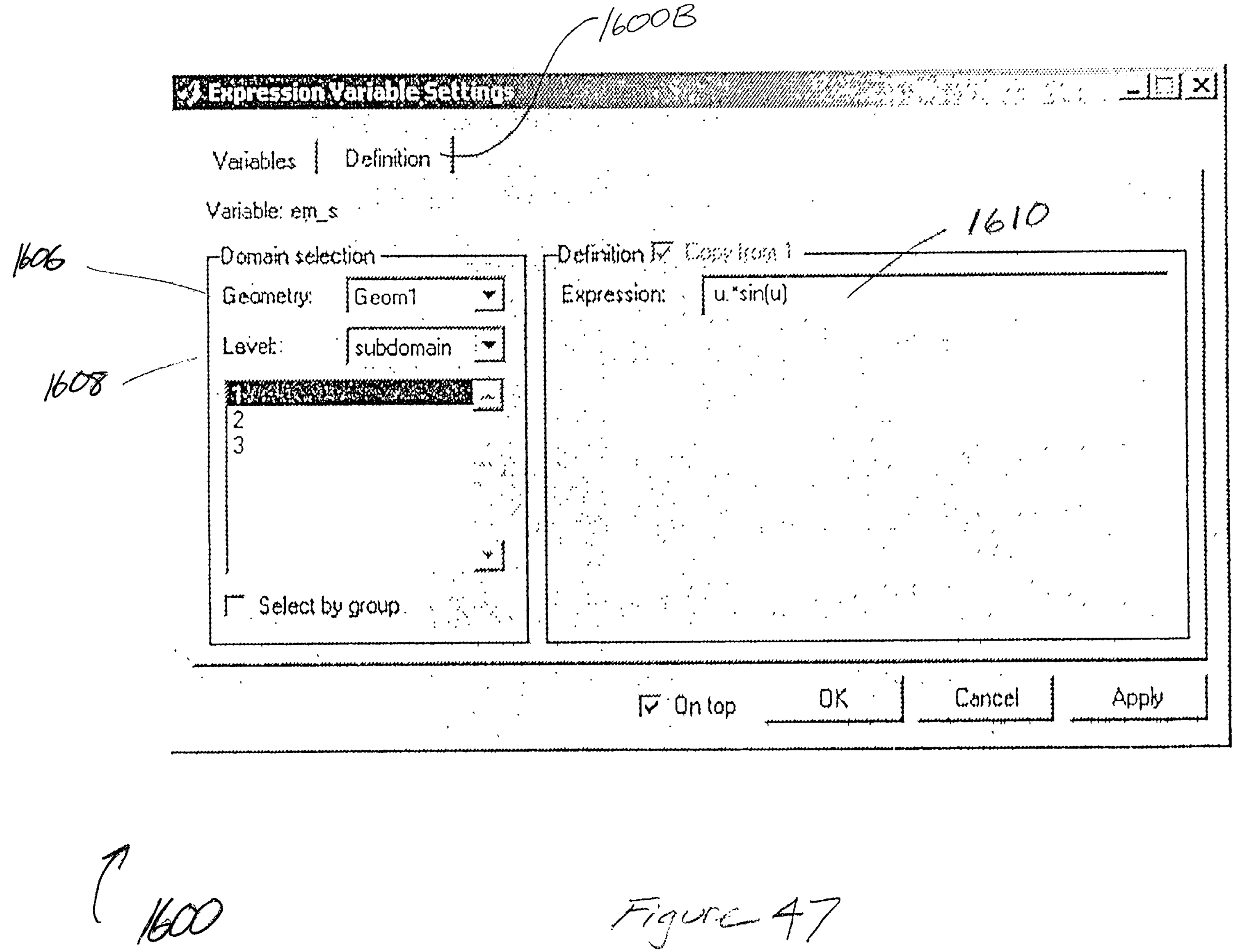

1600B
Expression Variable Settings
Variables
Definition
Variable: em_s
1606
1608
Domain selection
Geometry:
Geom1
Level:
subdomain
1
2
3
Select by group
1610
Definition
Copy from 1
Expression:
u.*sin(u)
On top
OK
Cancel
Apply
1600

Figure 47

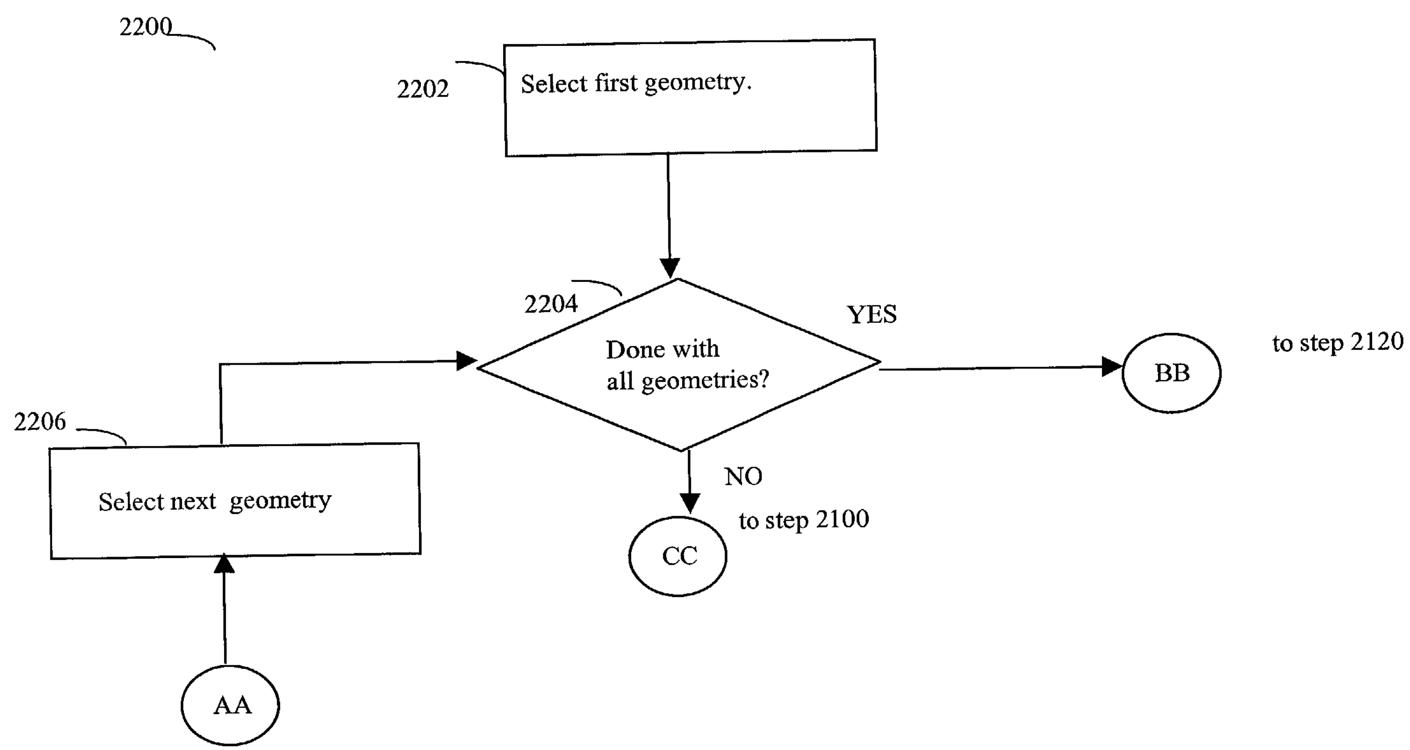

2200
2202
Select first geometry.
2204
Done with
all geometries?
YES
BB
to step 2120
NO
CC
to step 2100
2206
Select next geometry
AA

FIGURE 48

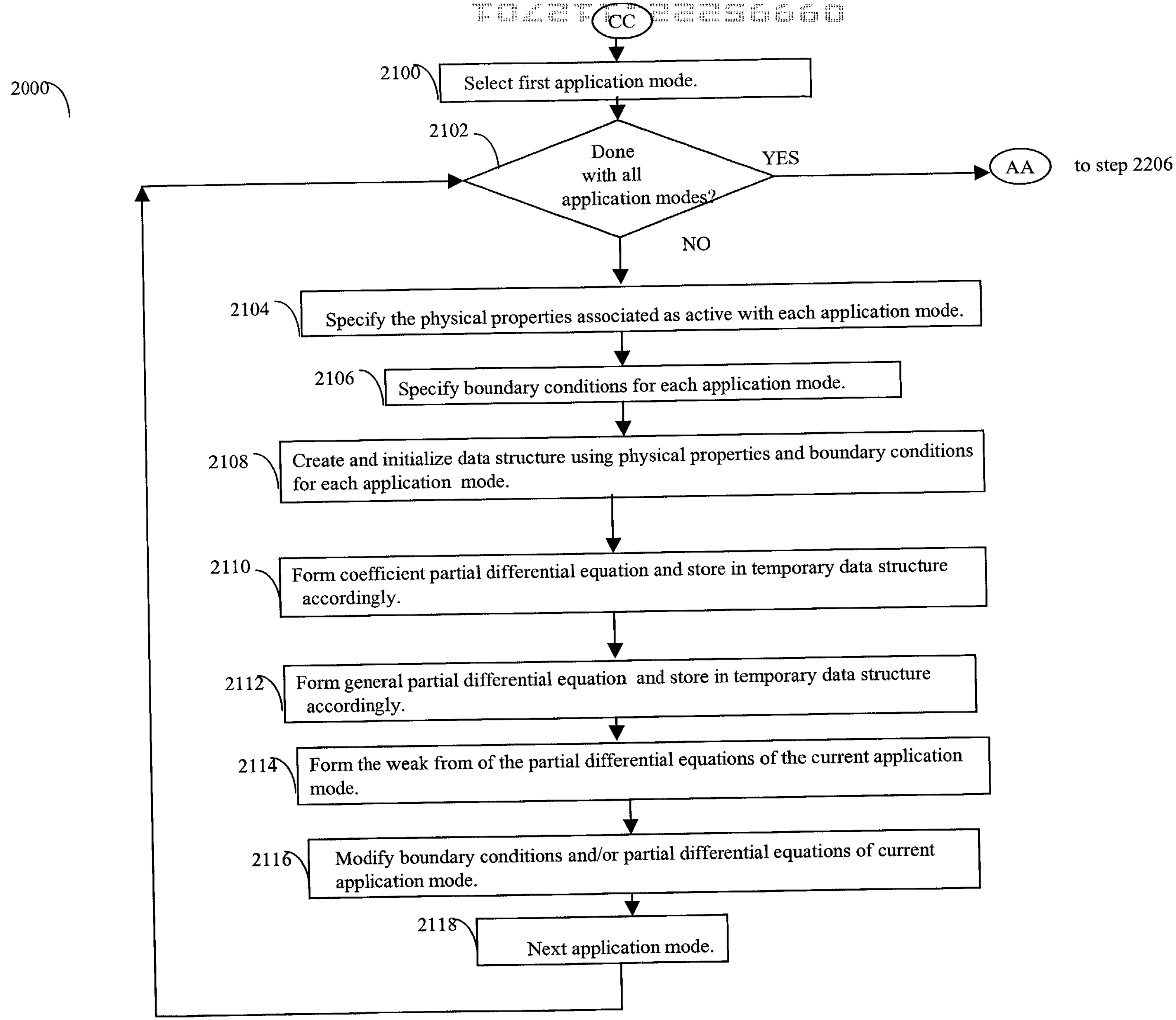

2000
CC
2100
Select first application mode.
2102
Done
with all
application modes?
YES
AA
to step 2206
NO
2104
Specify the physical properties associated as active with each application mode.
2106
Specify boundary conditions for each application mode.
2108
Create and initialize data structure using physical properties and boundary conditions for each application mode.
2110
Form coefficient partial differential equation and store in temporary data structure accordingly.
2112
Form general partial differential equation and store in temporary data structure accordingly.
2114
Form the weak from of the partial differential equations of the current application mode.
2116
Modify boundary conditions and/or partial differential equations of current application mode.
2118
Next application mode.

FIGURE 49

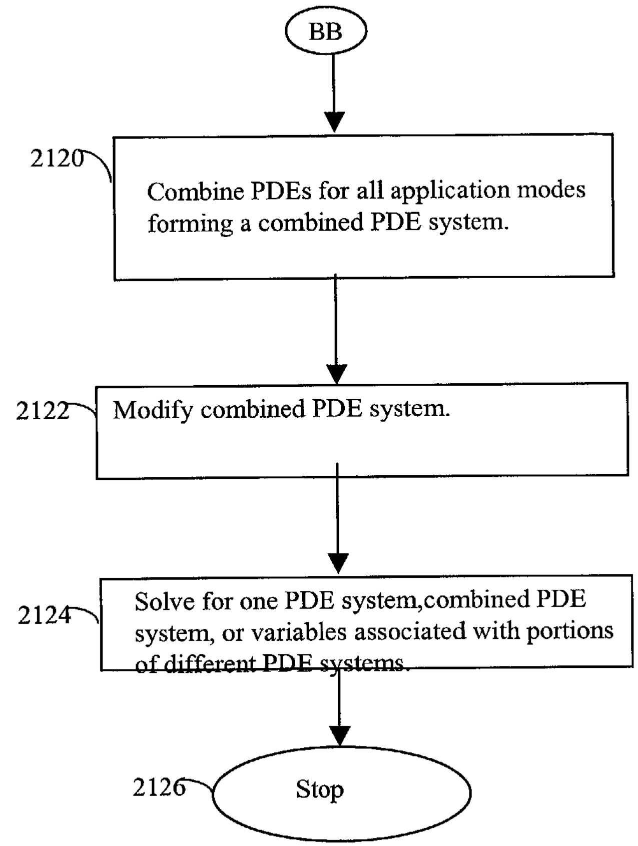

BB
2120
Combine PDEs for all application modes forming a combined PDE system.
2122
Modify combined PDE system.
2124
Solve for one PDE system,combined PDE system, or variables associated with portions of different PDE systems.
2126
Stop

FIGURE 50